AL/EQ-TR-1995-0013
Vol IV

ARMSTRONG LABORATORY

DEMONSTRATION AND EVALUATION OF THE AIR FORCE SITE CHARACTERIZATION AND ANALYSIS PENETROMETER SYSTEM IN SUPPORT OF NATURAL ATTENUATION INITIATIVES VOLUME IV - DEMONSTRATION, TESTING, AND EVALUATION AT DOVER AFB

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February 1996

Final Technical Report for Period October 1993 - December 1994

Approved for public release; distribution unlimited.

AIR FORCE MATERIEL COMMAND
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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT AVAILABLE FOR PUBLIC RELEASE DISTRIBUTION UNLIMITED
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) 5868	5. MONITORING ORGANIZATION REPORT NUMBER(S) AL/EQ-TR-1995-0013 Vol IV
6a. NAME OF PERFORMING ORGANIZATION APPLIED RESEARCH ASSOCIATES, INC. 6b. OFFICE SYMBOL (If applicable) ARA	7a. NAME OF MONITORING ORGANIZATION ARMSTRONG LABORATORY ENVIRONICS DIRECTORATE
6c. ADDRESS (City, State, and ZIP Code) RFD #1, BOX 120A WATERMAN ROAD SOUTH ROYALTON, VT 05068	7b. ADDRESS (City, State, and ZIP Code) AL/EQ-OL 139 Barnes Drive Suite 2 TYNDALL AFB, FL 32403-5323
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F08635-93-C-0020
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification) Demonstration and Evaluation of the Air Force Site Characterization and Analysis Penetrometer System in Support of Natural Attenuation Initiatives. Volume IV: Demonstration, Testing, and Evaluation at Dover AFB (Volume IV of V)

12. PERSONAL AUTHOR(S)
Martin L. Gildea, Wesley L. Bratton, Ph.D., James D. Shinn, II, P.E.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 10/93 TO 12/94	960209	

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A second-generation tunable Laser-Induced Fluorescence-Cone Penetrometer Test (LIF-CPT) system has been developed and demonstrated at three different Air Force Bases as an alternative site characterization technology. This represents an innovative technology for delineating soil contamination resulting from fuel spills. Applied Research Associates, Inc. and Dakota Technologies, Inc. jointly conducted the system development and demonstration project. Demonstrations consisted of 2-week efforts at each of Air Force Bases: Plattsburgh Patrick/Cape Canaveral, and Dover. The data collected during these demonstration supported both evaluation of the LIF-CPT systems along with support for selecting a site for a natural attenuation experiment the Air Force is [planning. Data analysis indicates that the second generation system is operationally improved over the first-generation system and has improved detection capabilities. The improved detection capability is related to a new optical module used to focus laser light and filter the return signal to reduce the signal-to-noise ratio. Although the system is improved in many ways, some questions still exist concerning the influence soil type has had on some of the system responses. Further analysis is required to resolve these discrepancies.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION
22a. NAME OF RESPONSIBLE INDIVIDUAL Bruce Nielsen	22b. TELEPHONE (Include Area Code) (904) 283-6227 / 22c. OFFICE SYMBOL EQW-OL

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

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PREFACE

This report was prepared by Applied Research Associates, Inc. (ARA), 120-A Waterman Road, South Royalton, VT 05068 under U. S. Air Force Contract No. F08635-93-C-0020, SSG Subtask 8.01.1 for the Armstrong Laboratory Environics Directorate, AL/EQW-OL, 139 Barnes Dr. Suite 2, Building 1120, Tyndall AFB, FL 32403-5323.

This final report discusses the continued development of the combined technology of the cone penetrometer (CPT) and laser-induced fluorescence (LIF) as it pertains to the detection and quantification of petroleum oils and lubricants (POL's) within subsurface soils environments. Specifically the report covers a review of LIF-CPT technology; LIF-CPT system specifications; evaluation of the LIF-CPT probe under field conditions; and LIF data analysis/evaluation. The data and results of the field investigations were subsequently used to determine if bioventing or natural attenuation approaches are viable remedial alternatives at three U.S. Air Force Bases.

The work was performed between October 1993 and December 1994. The AL/EQW project officer was Mr. Bruce Nielsen.

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EXECUTIVE SUMMARY

A. OBJECTIVE

Applied Research Inc. (ARA) and Dakota Technology, Inc. (DTI) were retained by the Armstrong Environics Directorate AL/EQ-QL to further develop laser-induced fluorescence-cone penetrometer technique (LIF-CPT) for use during environmental site investigations. The primary objective of the program was to develop and evaluate an improved LIF-CPT system for the characterization of fuel-contaminated sites. The evaluation was based on the results from demonstrations, testing and evaluation at three Air Force bases. A parallel goal of the demonstrations was to gather data for Engineering-Science, Inc. (E-S) to determine if bioventing or natural attenuation are viable alternatives for remediating numerous Air Force sites.

B. BACKGROUND

The Department of Defense (DoD) is seeking efficient and cost effective means to assess, remediate, and monitor petroleum-contaminated and hazardous waste sites at both active and decommissioned installations. The Air Force's Installation Restoration Program Information Management System (IRPIMS) database lists approximately 1,400 fuel-contaminated sites and 300 inactive firefighter training facilities; presently the IRPIMS database contains data from only one-half of the installations. Current environmental site investigations based on drilling technology are slow, expensive and potentially dangerous. Cone penetrometer (CPT) based investigations, on the other hand, allow real-time data collection and don't produce soil cuttings thus eliminating disposal costs and health and safety risks due to exposure.

Cone penetrometer testing gathers accurate in situ geotechnical information in a rapid and cost-effective manner. With adaptation of in situ geophysical and chemical sensors to the cone penetrometer probe, subsurface hydrogeology and the extent of contamination can be mapped simultaneously. The speed and continuous nature of the information generated by LIF-CPT reduces the need for costly and invasive subsurface sampling and installation of long term monitoring wells.

C. SCOPE

To fulfill the objectives of this project, the following tasks were completed; (1) Development, fabrication and integration of a field-deployable, wavelength-tunable LIF system, (2) Laboratory testing and evaluation of the LIF system, (3) Demonstration, testing and evaluation programs at Plattsburgh, Patrick/Cape Canaveral, and Dover Air Force Bases (AFB's), and (5) Delivery of a completed LIF system to the U. S. Army Corp. of Engineers.

Extensive evaluation and calibration of the LIF-CPT remained outside of the scope of this project. Such a study could not be completed during this project due to the dual objectives of

developing the LIF-CPT, and employing the tool and other CPT capabilities on a production basis for the engineering-cost evaluation conducted by E-S.

D. METHODOLOGY

The United State Army Corp of Engineers Waterways Experimental Station (USAE WES) initially developed the LIF-CPT using a mercury lamp as an excitation source downhole within the cone. The resulting fluorescence was collected and directed to a detection system located in the cone penetrometer truck via a single optical fiber. WES soon eliminated the mercury lamp in favor of a pulsed laser source external to the cone; a nitrogen laser system, limited to the emission of a single excitation wavelength of 337 nanometer (nm) was employed. This was useful for the detection of large multi-ring fuels such as Diesel Fuel Marine (DFM) but proved ineffective for "lighter" fuels such as jet fuels and gasoline which require excitation at shorter wavelength. Further research sponsored by the Air Force concluded that a tunable wavelength, pulsed laser (Nd:YAG) with a fiber optic probe and detection system would satisfy the needs of the Air Force. During the scope of the current program Applied Research Associates, Inc., in cooperation with Dakota Technology, Inc. (DTI), refined the Nd:YAG pulsed LIF-CPT system and demonstrated its utility in the field.

E. TEST DESCRIPTION

The test program consisted of two phases; (1) redesign and build a new laser system based on the findings of a previous LIF-CPT development program, and (2) evaluation of the LIF-CPT system under field conditions at three Air Force Bases. The redesign of the LIF-CPT system consisted of two major efforts: (1) optimizing the overall laser system performance by upgrading individual components with state-of-art components and repackaging the system improving portability and durability, (2) redesign the LIF-CPT probe to maximize the performance and durability and minimize cost. During the field demonstration and evaluation program several objectives were addressed. The primary technical focus was to evaluate the LIF-CPT system in the field for reliability, stability and repeatability, correlation of LIF-CPT intensity to contaminate concentration and evaluation of the sources of data scatter in the chemical and LIF-CPT data.

F. RESULTS

During the three demonstrations the laser system performed quite well. Many of the system improvements greatly enhanced both field utility and system stability. Minor improvements are still needed to enhance power stability, although the recording of the current power levels is highly beneficial.

Evaluation of the LIF response shows that there are effects related to both the soil type and moisture content of the materials being tested. The effect of soil type is fairly significant, since at some locations no LIF response was recorded in visibly contaminated clay samples. The effect of

moisture content is minimal. Further investigation into these responses would be highly beneficial. Finally, the limited data sets available permitted only speculation about possible correlations between LIF response and to be performed. The results form the statistical analysis are encouraging and additional testing performed.

G. CONCLUSIONS

In general the LIF and chemical analytical data agree well qualitatively. Evaluation of the limited chemical and LIF data indicates that their may be a correlation between total BTEX and Xylene concentrations and LIF response. The background limit of the LIF response was determined to be independent of the soil type but may have a weak dependency on moisture content. The background limit of the current LIF-CPT probe configuration is approximately 50 counts. There are still some unanswered questions regarding the response of the LIF system in different soils. Areas known to be highly contaminated showed little or no response in fine grained soils (e.g., silts and clays). Insufficient chemical data was available to fully validate the LIF system.

H. RECOMMENDATIONS

Additional data collection and evaluation is required to fully validate the LIF-CPT system. For future testing, it is strongly recommended that on-site analytical screening for Total Petroleum Hydrocarbons (TPH) by EPA method 418.1 be conducted on soil samples. This data can subsequently be used to correlate TPH concentration to LIF response. Combining objectives that include production-oriented data collection for other research is not recommended.

I. APPLICATION

The LIF-CPT system can be implemented by the Air Force as the primary technology to conduct environmental site assessments where petroleum, oils and lubricants are the contaminants of interest. It could be used both as an initial screening tool and/or as a tool to monitor the effectiveness of a particular remedial effort.

J. BENEFITS

Significant reductions in the time and cost of conducting environmental site assessments could be realized by implementing the LIF-CPT technology. This system provides superior data in real-time to use as a basis for selecting an appropriate remedial strategy.

K. TRANSFERABILITY OF TECHNOLOGY

Virtually all industrial contractors involved with subsurface environmental site assessments where petroleum oils and lubricants are concerned could profit from the use of LIF-CPT technology. The industry in general is constantly seeking ways to conduct business faster, cheaper, and better; CPT-LIF fulfills these criteria.

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SECTION I
INTRODUCTION

A. OBJECTIVE

The Armstrong Laboratory Environics Directorate (AL/EQ-OL) retained Applied Research Associates, Inc. (ARA) to demonstrate, test, and evaluate (DT&E) the application of the Air Force Site Characterization and Analysis Penetrometer System (AFSCAPS) in support of the Air Force's intrinsic remediation (natural attenuation) initiatives. One of the key components of the AFSCAPS involves the use of a Nd:YAG dye pumped laser system to induce fluorescence of fuel products as the CPT probe is advanced into the soils. Laser Induced-Fluorescence (LIF) has been shown to be useful in identifying petroleum, oil, and lubricant (POL) contamination.

ARA and their subcontractor, Dakota Technologies, Inc. (DTI), in cooperation with Engineering-Science, Inc. (E-S) and the 436 SPTG/CEV office at Dover Air Force Base, conducted an intensive subsurface investigation of soil and groundwater at the SS27/XYZ and D-7 sites located at Dover Air Force Base (AFB), Dover, Delaware. This investigation began 11 April 1994 and was completed on 21 April 1994. The dual objectives of this investigation were to:

- adequately assess the subsurface conditions to allow E-S to model the potential for natural attenuation using the Bio-Plume II numerical model, and

- demonstrate the CPT's capabilities to quickly locate and define the areal and vertical extent of the liquid-phase plume using LIF, and to rapidly install monitoring points and collect soil samples to provide additional data necessary to define the dissolved-phase plume.

This data report contains a brief description of the site, data obtained and a brief interpretation of the data. A more detailed analysis of the LIF and analytical laboratory data will be presented in a later report.

B. BACKGROUND

2. CPT Capabilities

Historically, the cone penetrometer has been employed as an expeditious and effective means of analyzing the lithology of a site by measuring the resistance of different soil types against the penetrometer probe as it is advanced into the subsurface. ARA has expanded the CPT's capabilities in several ways to allow further definition of the subsurface environment.

The DTI Nd:YAG laser system was integrated into the CPT by ARA and DTI to locate fuel contamination using the LIF response of the soil/fuel mixture. Subsequently, the LIF response can be correlated to the total petroleum hydrocarbon (TPH) concentration present within the soil. To date, the LIF laser system's primary function has been to define the liquid phase plume.

To aid in defining the dissolved-phase plume, ARA has developed a rapid method of installing small-diameter (0.5-inch) monitoring wells. These wells are typically installed based upon the LIF-CPT data and can be installed to any desired depth with a screened interval typically ranging between 1 to 2 meters. Experience has demonstrated that these wells perform well in aquifers where the depth to the potentiometric surface (water table under unconfined conditions) does not exceed the capacity of a vacuum pump (typically about 25 feet below grade).

Collection of soil samples serves several purposes. First it provides a physical specimen with which the CPT data can be correlated. In essence, it allows the observer to look at the CPT cone tip and sleeve stresses combined with the pore water pressure data indicated on the CPT logs and compare it directly with the in situ soils. This allows for accurate interpretation of the CPT logs and subsequent interpretation of the overall site lithology. Secondly, subsequent chemical analysis of the soil samples for total petroleum hydrocarbons (TPH) provides a correlation between LIF data and the in situ TPH concentrations. Finally, additional chemical analysis of the soil samples provides other required data to effectively model the natural attenuation potential of the site using the Bioplume II numerical model.

SECTION II
SITE DESCRIPTION

The efforts of this investigation were primarily devoted to the SS27/XYZ site (Figure 1, Site Map). A limited investigation was conducted at the D-7 landfill area that involved the installation of three nested well pairs (shallow and deep). Because of the limited amount of data collected at this location, it will not be discussed further. The background sections pertaining to the site geology, hydrogeology, and soil and groundwater quality were extracted from the work plan developed by Engineering-Science, Inc. for this site (Ref. 1).

A. SITE GEOLOGY AND HYDROGEOLOGY

Dover AFB is located in the Atlantic Coastal Plain Physiographical Province, a wide wedge-shaped belt of Cretaceous to Recent sedimentary deposits of gravel, sand, silt, clay, limestone, chalk, and marl that dip to the southeast (Ref. 2). Approximately eight sedimentary formations exist under Dover AFB extending as much as 1400 feet below the ground surface. These formations are typified by various lithologies including: sand, gravel, fine to coarse sand, silt, clay, glauconitic sand, glauconitic silts, glauconitic-silty clay, interbedded clay, and variegated clay. The Columbia Formation, which starts at grade and dominates the near surface geology in Delaware, was deposited under fluvial conditions, forming a broad sheet-like deposit of sand. This unconfined, water-bearing sand layer is characterized by reddish-brown to tan, yellow, or light-gray, poorly sorted coarse-to-medium-grained sand and gravel, with interbedded silt and clay lenses. The thickness of the Columbia aquifer under Dover AFB typically ranges from 25 to over 70 feet.

Site SS27/XYZ is situated on a portion of the Columbia Formation that is characterized by fine-to-medium-grained sand that coarsens into coarse, to very coarse with depth. Laterally discontinuous lenses of clay and gravel are also present. The thickness of the Columbia Formation ranges from 25 to 35 feet under the fueling pads at site SS27/XYZ and groundwater elevations range from approximately 13.9 to 15.6 feet MSL. Estimates of the groundwater flow velocity at site SS27/XYZ were based on pump test data from site D-5, located about 2 miles east, and are approximately 0.29 foot/day, or 106 feet/year. A groundwater divide runs parallel to, and under

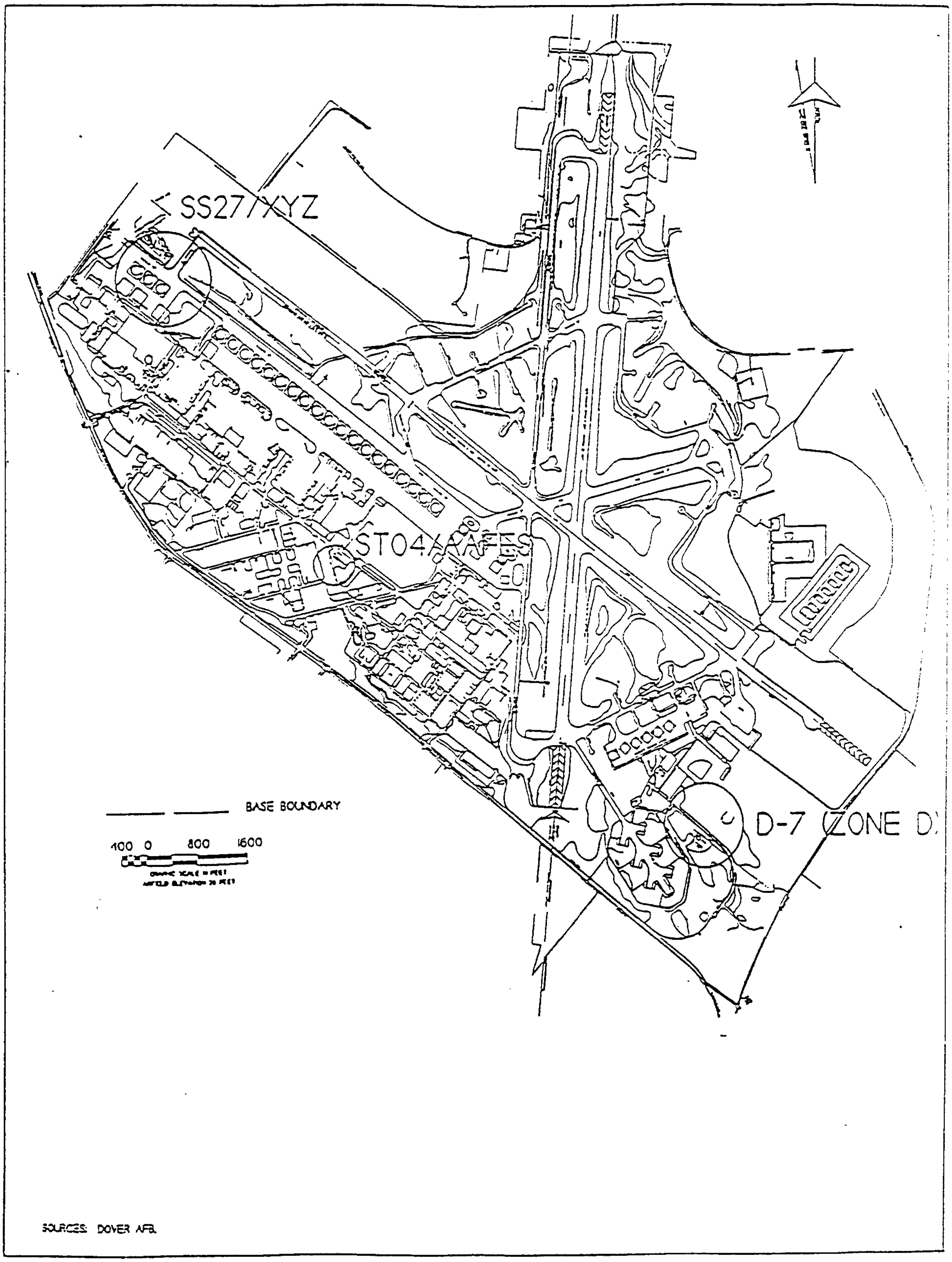

Figure 1. Site map of Dover AFB, Delaware.

the NW/SE runway next to site SS27/XYZ. This groundwater divide is apparently the result of extensive runway coverage, which inhibits surface water infiltration of large volumes of fill material used in runway construction. Because of Site SS27's nearness to the groundwater divide, the direction of groundwater flow may switch during seasonal fluctuations in rainfall. However, the average flow of groundwater appears to be in a southwest direction with a gradient of 0.0022 foot/foot.

1. Soil Quality

Characterization of the vadose zone and shallow Columbia aquifer system at site SS27/XYZ has been the objective of several site investigations. To date, four (4) sediment samples have been taken by SAIC (Ref. 3 and Ref. 4). A soil gas survey completed by SAIC in 1989 (Ref. 4) included 32 measurements across the site. An additional soil gas survey was performed by Dames & Moore in 1993 (Ref. 5) that included a grid of sampling points covering an area approximately 400 by 2,400 feet between the NW/SE runway and the fueling pads. An estimated 75 measurements of soil gas were taken.

The results of the second soil gas study revealed that most of the petroleum hydrocarbon contamination at site SS27/XYZ is along the fuel lines, though the isocontours for total volatile organic compounds (VOCs) appear to extend beneath the fuel pad. Soil gas study results also indicate that hydrocarbon contamination at the site is high, though not as spatially extensive as reported in previous studies (Ref. 4). Oil and grease concentrations in the soil at the site ranged from 2.5 to 65 mg/kg (Ref. 3), and soils also contained minor amounts of lead (5 mg/kg).

2. Groundwater Quality and Chemistry

Previous investigations of site SS27/XYZ detected plumes of benzene (1.4 to 7,000 μg/L), o-xylene (11 to 870 μg/L), ethylbenzene (1.3 to 2,200 μg/L), and toluene (0.3 to 680 μg/L) originating at the JP-4 fuel pipelines extending from Building 950. The most recent investigation of VOCs in the groundwater was conducted by Dames & Moore (Ref. 5). Results indicate that areas of groundwater contamination coincide with earlier detections of fuel contamination in soil gas. These results are presented in detail in HAZWRAP 1993b. (Ref. 5)

SECTION III
RESULTS

During the course of this investigation, ARA completed a total of 29 CPT soundings, 26 that included LIF analysis. Figure 3 depicts the locations of these soundings. Based upon this data, 33 successful monitoring wells were installed to various depths to allow collection of groundwater samples for subsequent chemical analyses. In addition, 10 soil samples were obtained to provide additional data required for the Bioplume II modeling and to allow correlation with both the CPT and LIF profiles. A summary of soundings completed and respective well completion details and soil sampling intervals is included in Table 1.

A. INTERPRETATION OF LIF-CPT PROFILES

Inspection of the CPT profiles indicate that the overburden soils at the SS27/XYZ site consist of interbedded clays, silts, sands and gravels, and mixtures thereof. This interpretation is in good agreement with findings from previous investigations. The basis for this interpretation is presented below.

Comparison of tip stress, friction ratio and penetration pore pressure profiles are the most important parameters for estimating soil type and stratigraphy from CPT data. The magnitude of the tip resistance is a function of the strength of the soil, with stronger materials having higher tip resistances. Tip resistance also increases as the coarse grained soil content increases, and decreases as the fine grained content increases. The degree of consolidation of the soils can influence tip resistance with both the tip and sleeve stresses increasing as the degree of consolidation increases. Overconsolidation can be caused by previous loading of the soil or desiccation. For a given soil, the tip stress increases with depth due to the increase in geostatic stresses.

The friction ratio is a good indicator of the cohesiveness of the soil, which in turn reflects the fine grained soil content. Soils that are predominantly fine grained have friction ratios generally greater than 2, and sandy soils have ratios of 2 or less. Weak and sensitive clays will have friction ratios of less than 2. The penetration pore pressure response is a function of the soil's shear

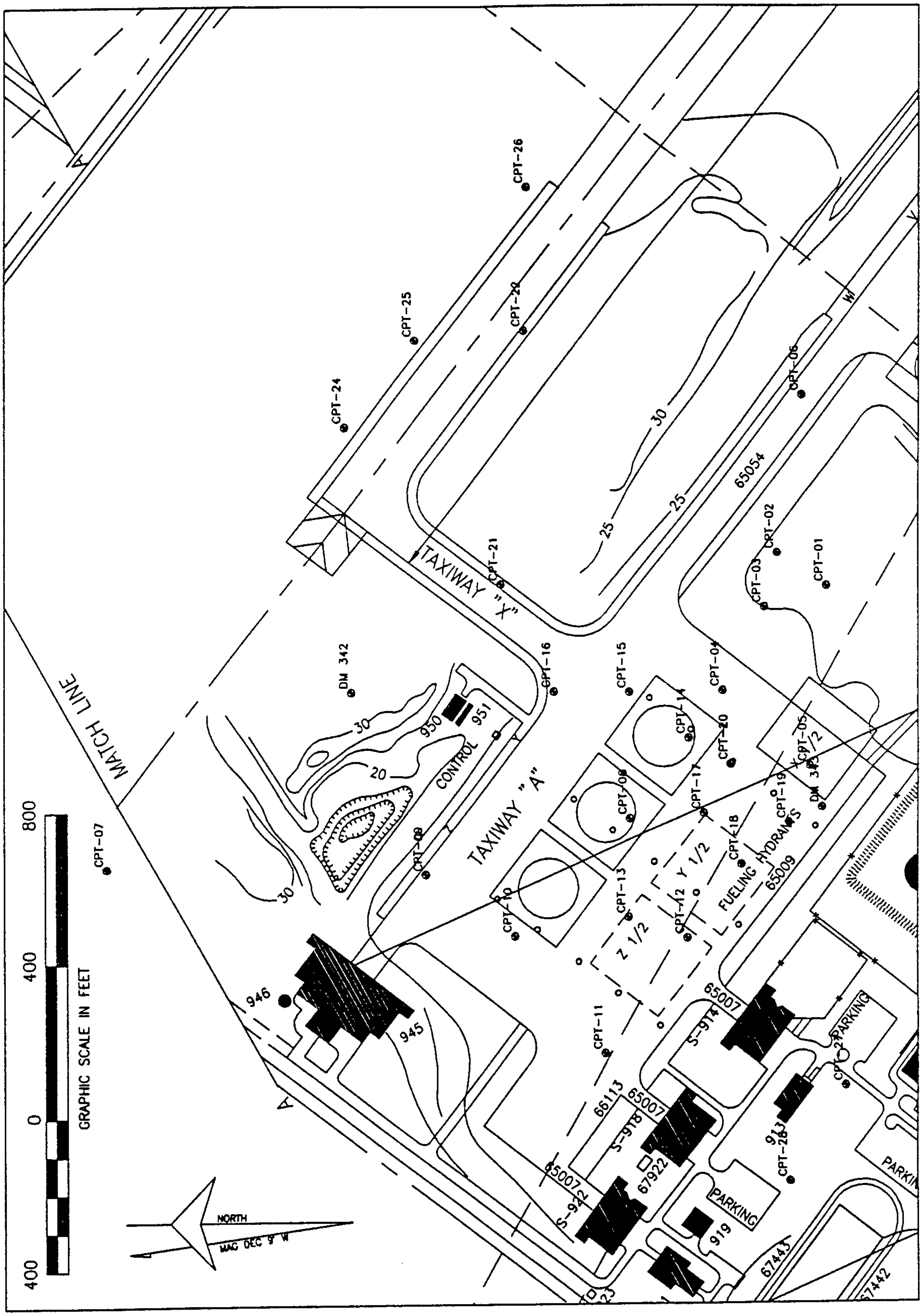

Figure 2 Locations of LIF-CPT Soundings Conducted at the SS27/XYZ Site, Dover AFB, Delaware.

Table 1 LIF-CPT SUMMARY.

ID CPT	Soil Unit	MP or SC	Depth Interval	Casing Dia. (in.)	Compt Type	Comments
1	S	MP	13.6-16.9	0.5	P	
2	S	MP	9.6-12.9	0.5	T	
3	S	MP	9.6-12.9	0.5	T	
4	S	MP	13.6-16.9	0.5	T	
5	-	NONE	-	-	-	
6	S	MP	13.2-16.5	0.5	P	
	D	MP	20.5-23.8	0.5	-	Destroyed; Abandoned
7	S	MP	11.6-14.9	0.5	T	
	D	MP	24.8-28.1	0.5	T	
	-	SC	16.0-13.0	-	-	
8	Perched	MP	8.7-12.0	0.5	-	No Yield; Abandoned
	S	MP	13.2-16.5	0.5	P	
	D	MP	24-27.2	0.5	P	
	-	SC	8.0-10.0	-	-	
	-	SC	13.7-15.7	-	-	
9	S	MP	11.9-18.5	0.5	P	
10	S	MP	11.9-18.5	0.5	T	
11	Perched	MP	9.6-12.9	0.5	T	
	S	MP	15.4-18.7	0.5	T	
12	Perched	MP	8.6-11.9	0.5	-	No yield; Abandoned
	S	MP	14.4-17.7	0.5	P	
	D	MP	20.0-23.3	0.5	P	
	-	SC	14.0-16.0	-	-	
13	S	MP	13.9-17.2	0.5	T	
14	S	MP	13.5-16.8	0.5	P	
	WT	MP	7.5-17.5	1.5	-	Wrong depth; Abandoned
	-	SC	7.0-9.0	-	-	No Recovery
	-	SC	13.0-15.0	-	-	

KEY:

S = Shallow Aquifer — T = Temporary

D = Deep Aquifer — P = Permanent

MP = Monitoring Point — WT = Water Table

SC = Soil Core — Perched = Perched W

Table 1 LIF-CPT SUMMARY
(concluded).

ID CPT	Soil Unit	MP or SC	Depth Interval	Casing Dia. (in.)	Compt Type	Comments
15	S	MP	14.5-17.8	0.5	T	
16	S	MP	10.0-13.3	1.5	-	Wrong depth; Abandoned
	S	MP	10.0-13.3	0.5	P	
	D	MP	20.7-24.0	0.5	P	
	-	SC	7.0-9.0	-	-	
	-	SC	11.0-13.0	-	-	
17	S	MP	15.4-18.7	0.5	T	
18	S	MP	12.0-18.6	0.5	T	
19	Perched	MP	6.7-10.0	1.5	-	No yield; Abandoned
	S	MP	12.5-15.8	1.5	-	No yield; Abandoned
	S	MP	12.5-15.8	0.5	P	
	D	MP	22.7-26.0	0.5	P	
	-	SC	9.0-11.0	-	-	
	-	SC	15.0-17.0	-	-	
20	S	MP	12.0-15.3	0.5	T	
21	S	MP	11.5-14.0	0.5	T	
22	S	MP	14.5-17.8	0.5	P	
	D	MP	27.0-30.3	0.5	P	
	-	SC	13.0-15.0	-	-	
23	-	-	-	-	-	Refusal at 7 ft.
24	S	MP	12.2-15.5	0.5	-	No yield; Abandoned
25	S	MP	17.5-20.8	0.5	P	
26	S	MP	16.5-23.1	0.5	P	
27	S	MP	14.0-17.28	0.5	P	
	D	MP	25.0-28.28	0.5	P	
28	S	MP	17.0-20.28	0.5	P	
29	S	MP	-	0.5	T	
D7CPT01	S	MP	17.5-20.78	0.5	T	
	D	MP	38.22-41.5	0.5	T	
D7CPT02	S	MP	20.0-23.28	0.5	T	
	D	MP	38.22-41.5	0.5	T	
D7CPT03	S	MP	-	0.5	T	
	D	MP	-	0.5	T	

KEY:

S = Shallow Aquifer
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Perched = Perched W

strength and stiffness, hydraulic conductivity and density. For normally consolidated soils, the penetration pore pressure will be greater than the static pore pressure for clays and silts, and equal to the static pore pressure for clean sands. In overconsolidated, dense soils the pore pressure response can be less than the static pore pressure, especially in those soils that tend to dilate, such as silty sands. The combination of the friction ratio and pore pressure response provides a good identification of the soil stratigraphy. With this basic understanding of the P-CPT data, an analyst can interpret the stratigraphy and soil types visually as described below.

A typical penetration profile from Dover AFB is presented in Figure 4a. This profile (XYZCPT14-LIF) was completed to a depth of 22.5 feet and is representative of the geologic conditions at Dover AFB. This profile includes the sleeve stress, tip resistance, friction ratio, penetration pore pressure, and baseline LIF counts measured during the test, along with the soil classification and soil stratigraphy calculated from the data. For location XYZCPT14-LIF, the friction ratio profile is variable, which indicates that the deposits consist of stratified clays, silts and sands, and mixtures thereof down to approximately 13.5 feet. Between 13.5 feet and 19 feet there appears to be a lens of silty sand showing a maximum density at about 16.5 feet. Based on the tip stress, the density decreases uniformly from 16.5 to approximately 19.3 indicating a looser/softer material. From 19.3 to 20.8, the log indicates a stratified sand/clay/silty clay material. This can be clearly seen from the rapid increase in pore water pressure caused by the displacement of the soil by the cone. The pore water pressure increases above the static pressure because the hydraulic conductivity of the fine-grained soil does not allow the pressure to dissipate rapidly. From 20.8 feet to 22.5 the density once again begins to climb, and although not illustrated on this log, previous soundings typically indicated that this is the beginning of a dense gravel lens.

The LIF data accumulates at a rate of approximately 1 waveform per second, which correlates to 1waveform every 2 centimeters as the LIF sensor is advanced into the formation. A typical LIF profile is plotted in Figure 4b. Each waveform consists of 125 data points and, when integrated, yields the LIF intensity value at a particular depth. The LIF data files showed a baseline-shift apparently due to background noise from various sources. To compensate for this shift, the data sets were modified by subtracting out the average of the first five data points in each waveform before integration. This produces a waveform with a zero baseline. To compensate for power shifts from one location to the next, the LIF profile is further modified. The median of the

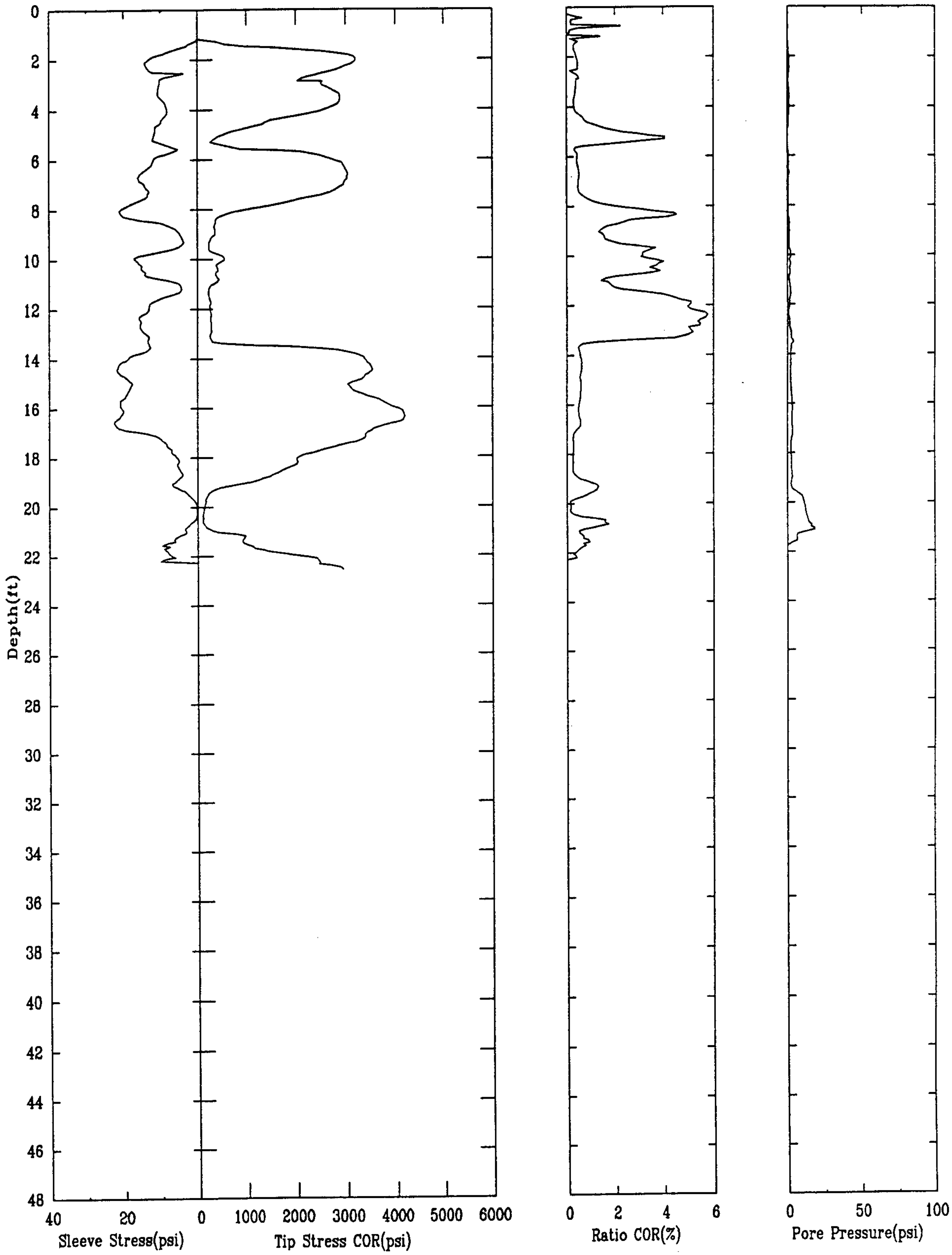

Figure 3. LIF-CPT profiles for XYZCPT-14-LIF.

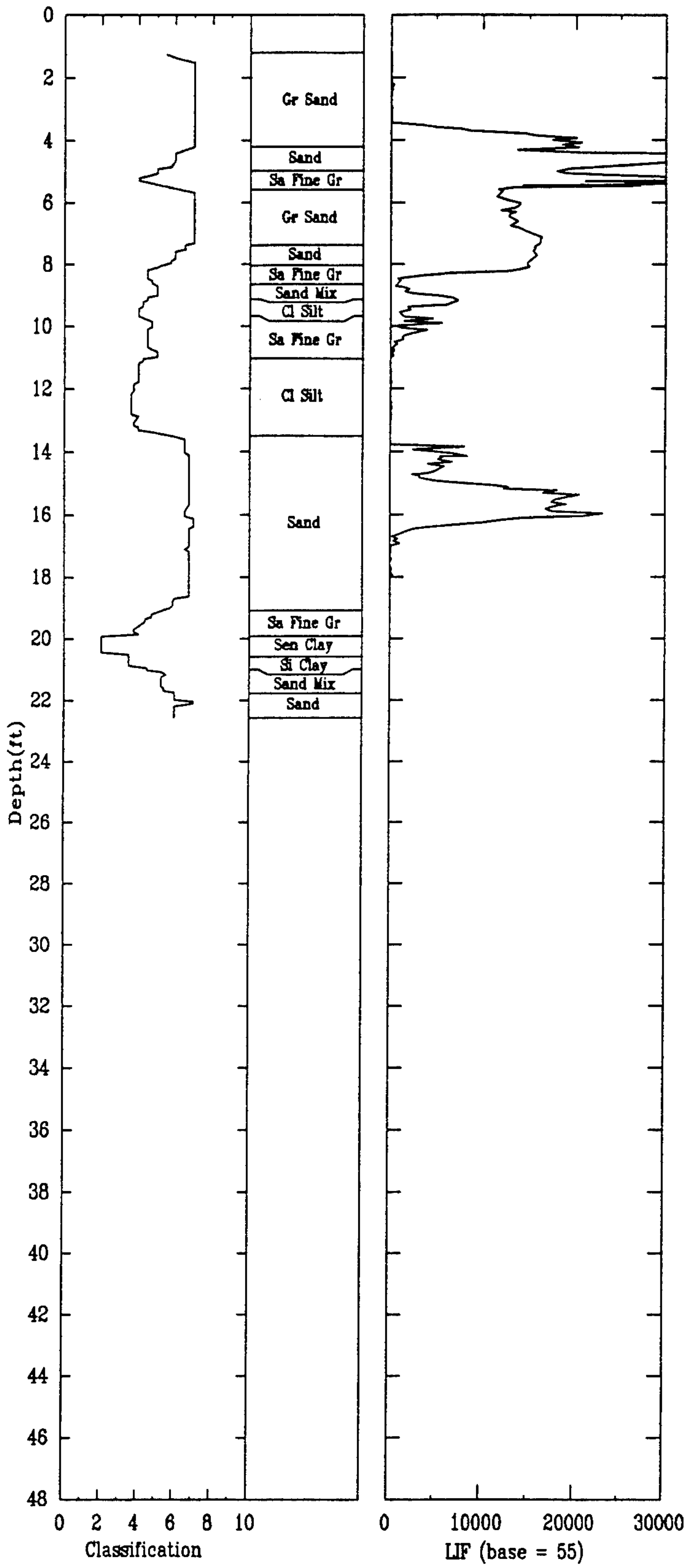

Figure 3a. LIF-CPT profiles for XYZCPT-14-LIF (concluded).

lowest 41 LIF intensity values is subtracted from all LIF values in that profile. This number is called the time base for that profile. The data are subsequently plotted incorporating the above modifications.

The LIF profile for XYZCPT14-LIF (Figure 4b) shows a significant response beginning at approximately 3.5 feet below ground surface (bgs). Maximum values greater than 30,000 LIF units were noted in the sand seam between 4.3 and 5.5-feet bgs. This response is equivalent to the response of liquid phase JP-4 used to calibrate the laser. The LIF response continues to decrease reaching the baseline value (55 units) at 11 feet bgs. This depth coincides precisely with sand (fine grain)/clayey silt interface. Studies have shown that high clay content can attenuate LIF response that may explain this result. At 13.6 feet bgs and in a sand layer the LIF response again shows a significant response, albeit lower than above. The response increases to a maximum value at 16 feet bgs, then decreases to baseline at approximately 17 feet bgs. No further response was noted in this profile.

All of the profiles of the LIF-CPT soundings are included in Appendix A.

SECTION IV
CONCLUSIONS

The LIF-CPT proved a useful and efficient tool for conducting a subsurface site investigation at the SS27/ XYZ site located at Dover AFB, in Dover, Delaware. The CPT data accurately described the lithology of the site as interbedded clays, silts, sands, and gravels as well as mixtures thereof. This interpretation closely matches interpretations described by others during previous investigations. The CPT data were used to effectively set monitoring wells and collect soil samples. The LIF data assisted in defining both the horizontal and vertical extent of the liquid phase plume. A complete anal[illegible] report assessing all the data collected during the course of this investigation, including the gro[illegible]ater and soil chemical analytical data, is contained in Volume I.

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1. "Work Plan for an Engineering Evaluation/Cost Analysis in Support of the Intrinsic Remediation (Natural Attenuation) Option," *Engineering-Science, Inc.*, April 1994.

2. Foster, M.D., 1950. "The origin of High Sodium Bicarbonate Waters in the Atlantic and Gulf Coastal Plains," *Geochimica et Cosmichimica Acta*, Vol. 1, pps. 33-48.

3. Science Applications International Corporation (SAIC), 1986. USAF Installation Restoration Program - Dover AFB, Delaware, Phase II - Stage I Confirmation/Quantification.

4. Science Applications International Corporation (SAIC), 1986. USAF Installation Restoration Program - Dover AFB, Delaware.

5. HAZWRAP, 1993b. Ecological Risk Assessment, Phase I: Site Characterization; Dover Air Force Base, Dover, Delaware, submitted by Dames & Moore, February 2, 1993.

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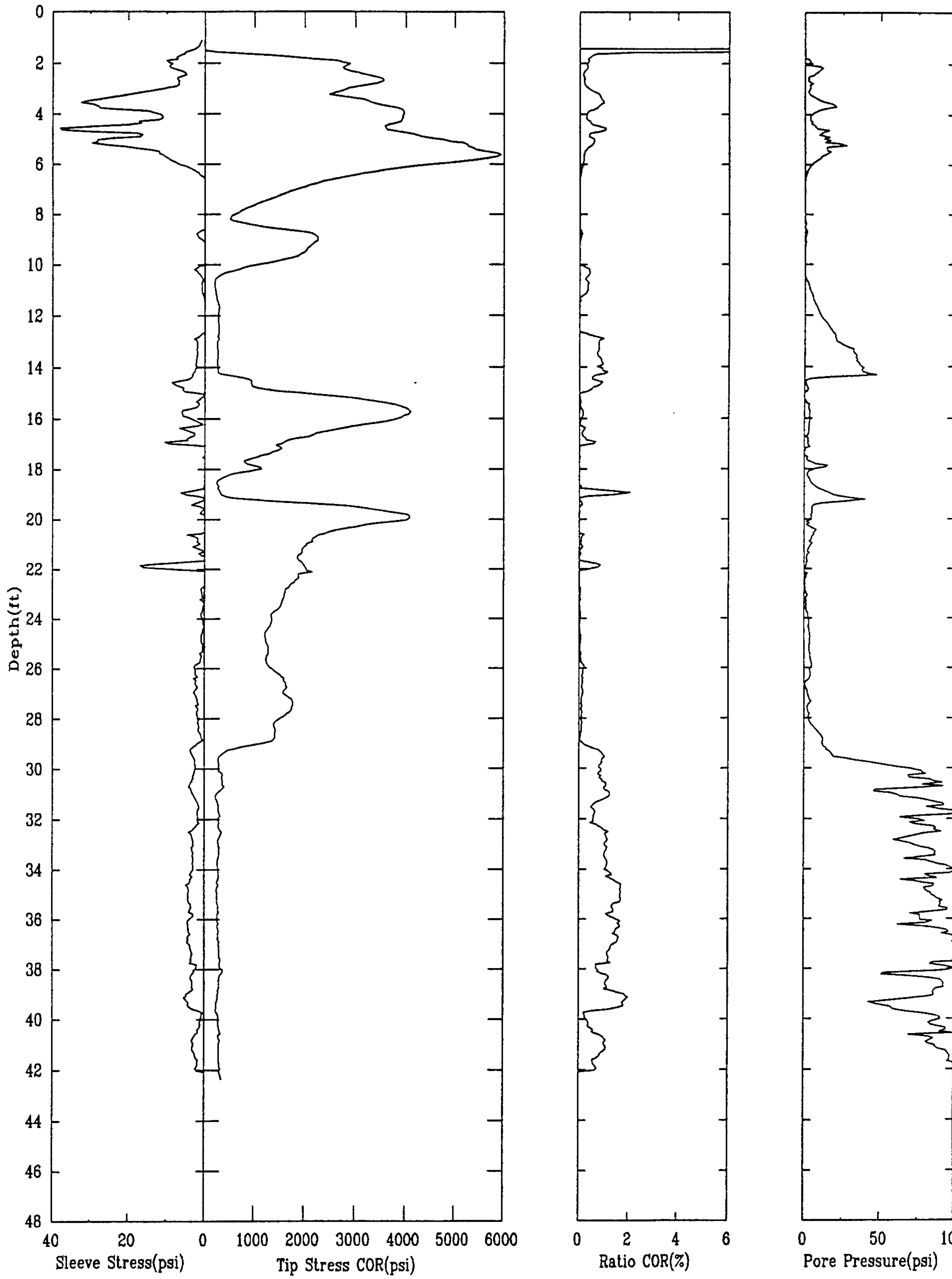
APPENDIX A

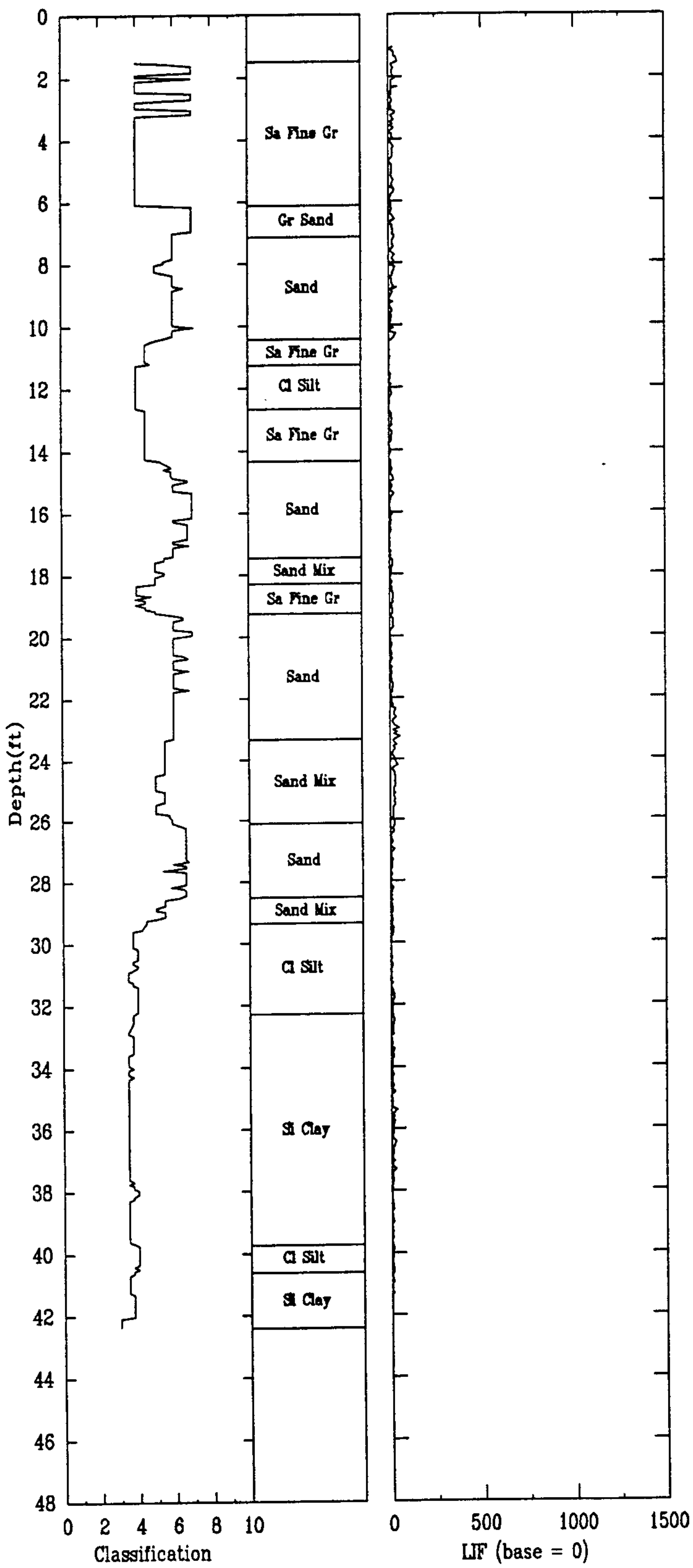
XYZ-CPT-01-LIF APPLIED RESEARCH ASSOCIATES, INC. 04/11/94

Dover Air Force Base



XYZ-CPT-01-LIF APPLIED RESEARCH ASSOCIATES, INC. 04/11/94

Dover Air Force Base



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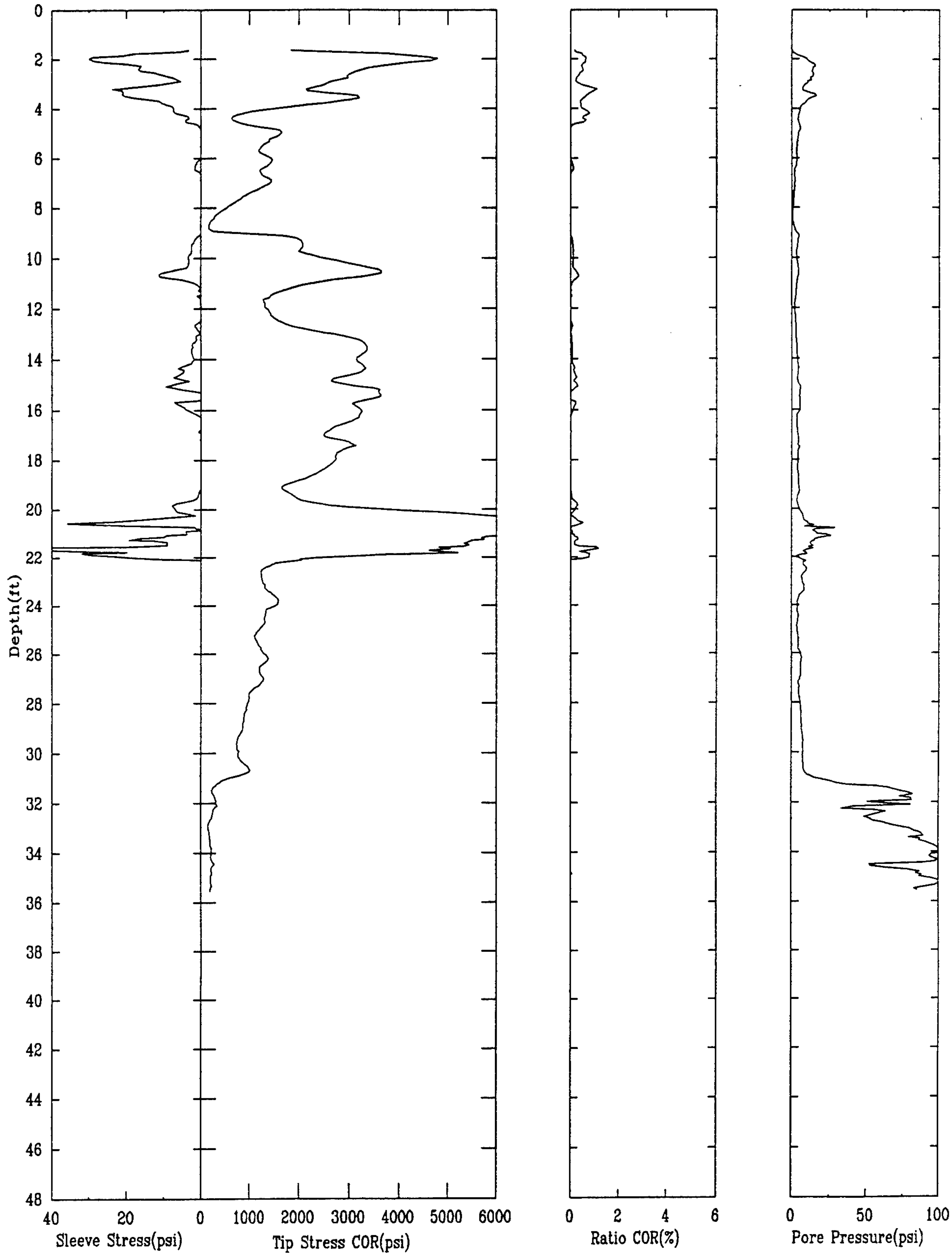

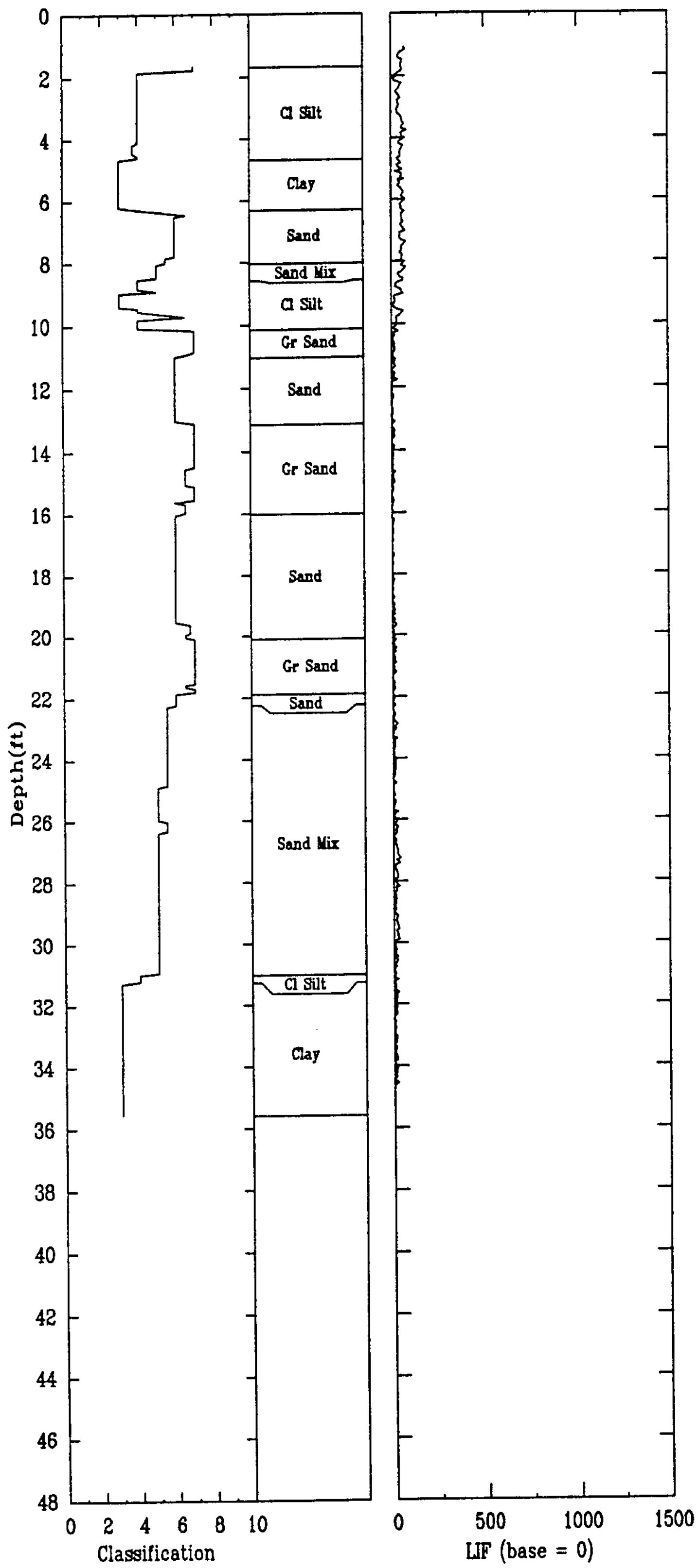
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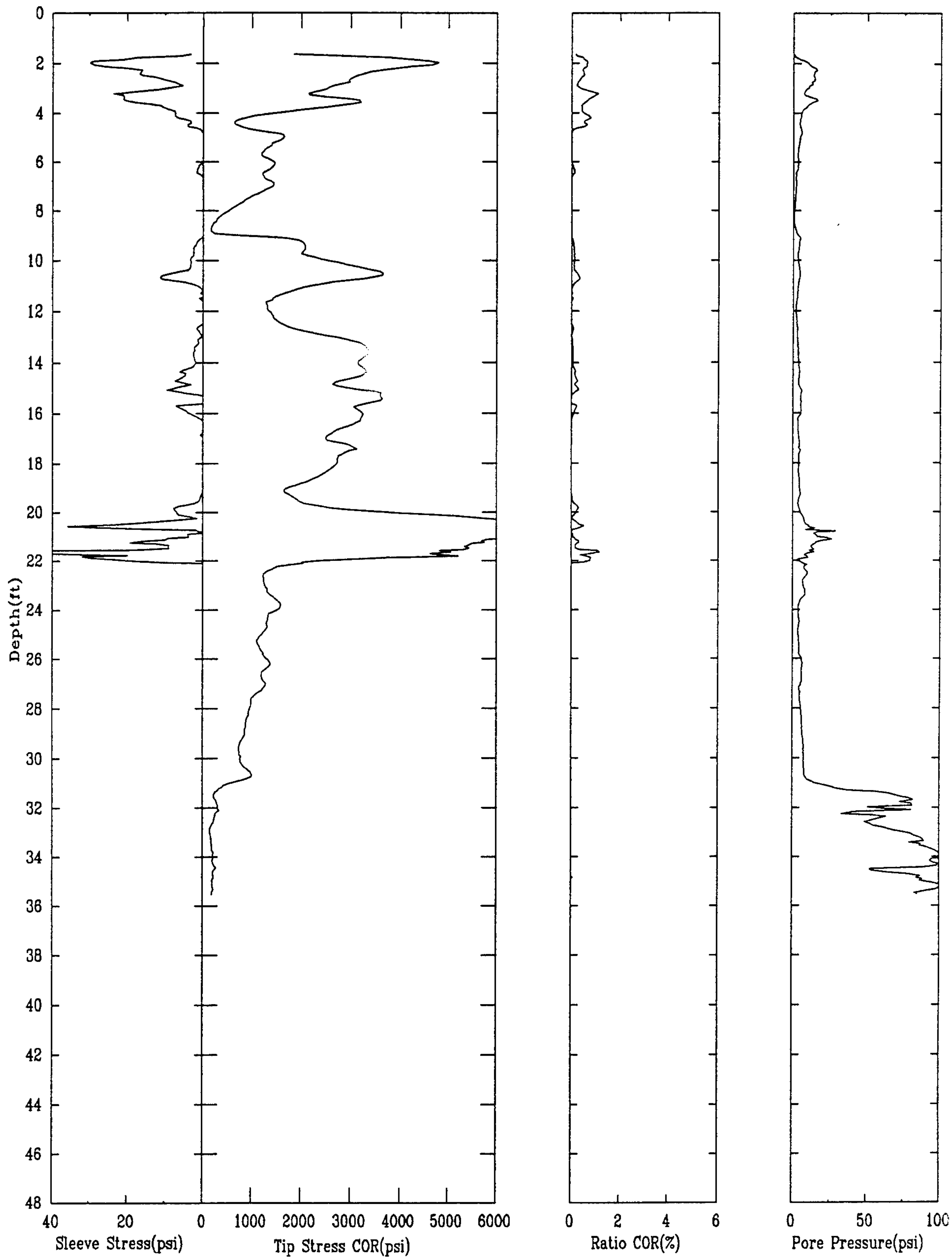
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
Cl Silt
Clay
Sand
Sand Mix
Cl Silt
Gr Sand
Sand
Gr Sand
Sand
Gr Sand
Sand
Sand Mix
Cl Silt
Clay
0 2 4 6 8 10
Classification
0 500 1000 1500
LIF (base = 0)

Dover Air Force Base



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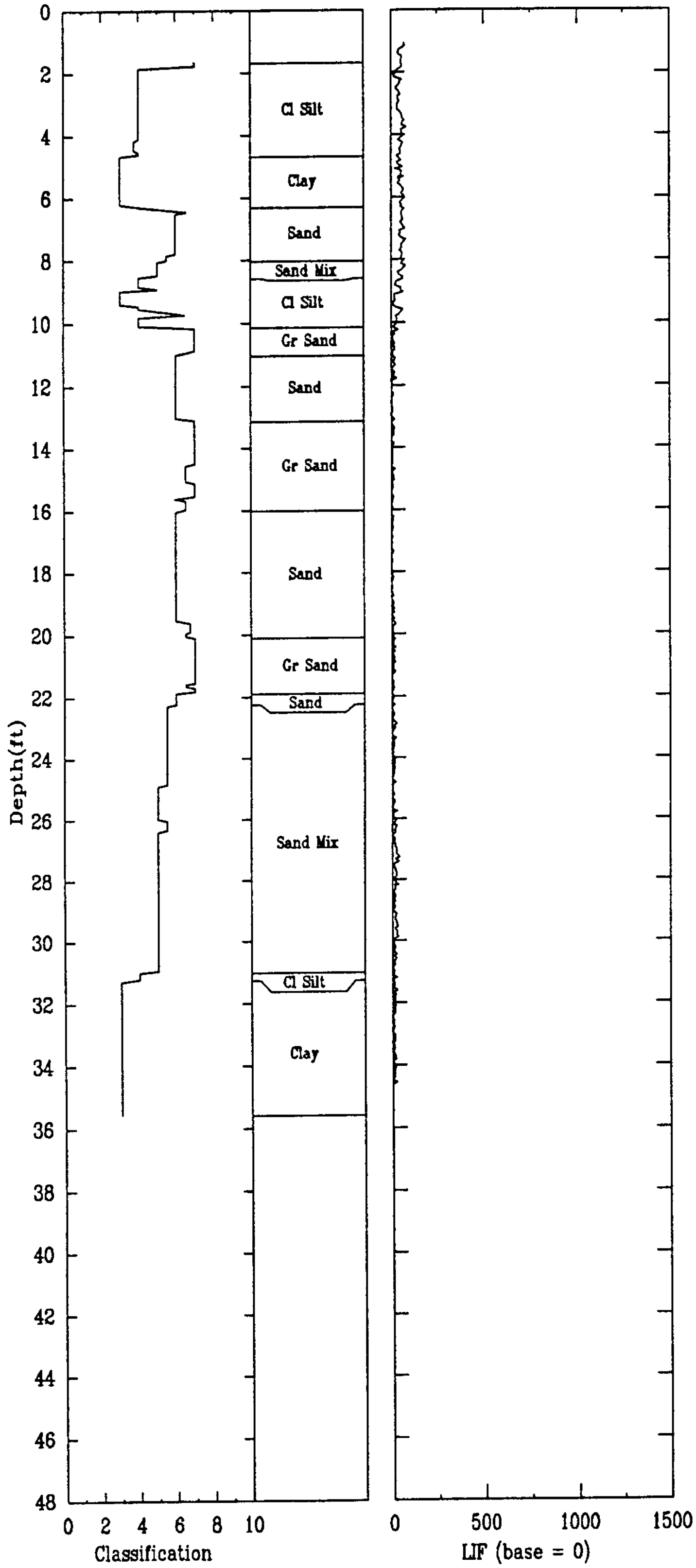

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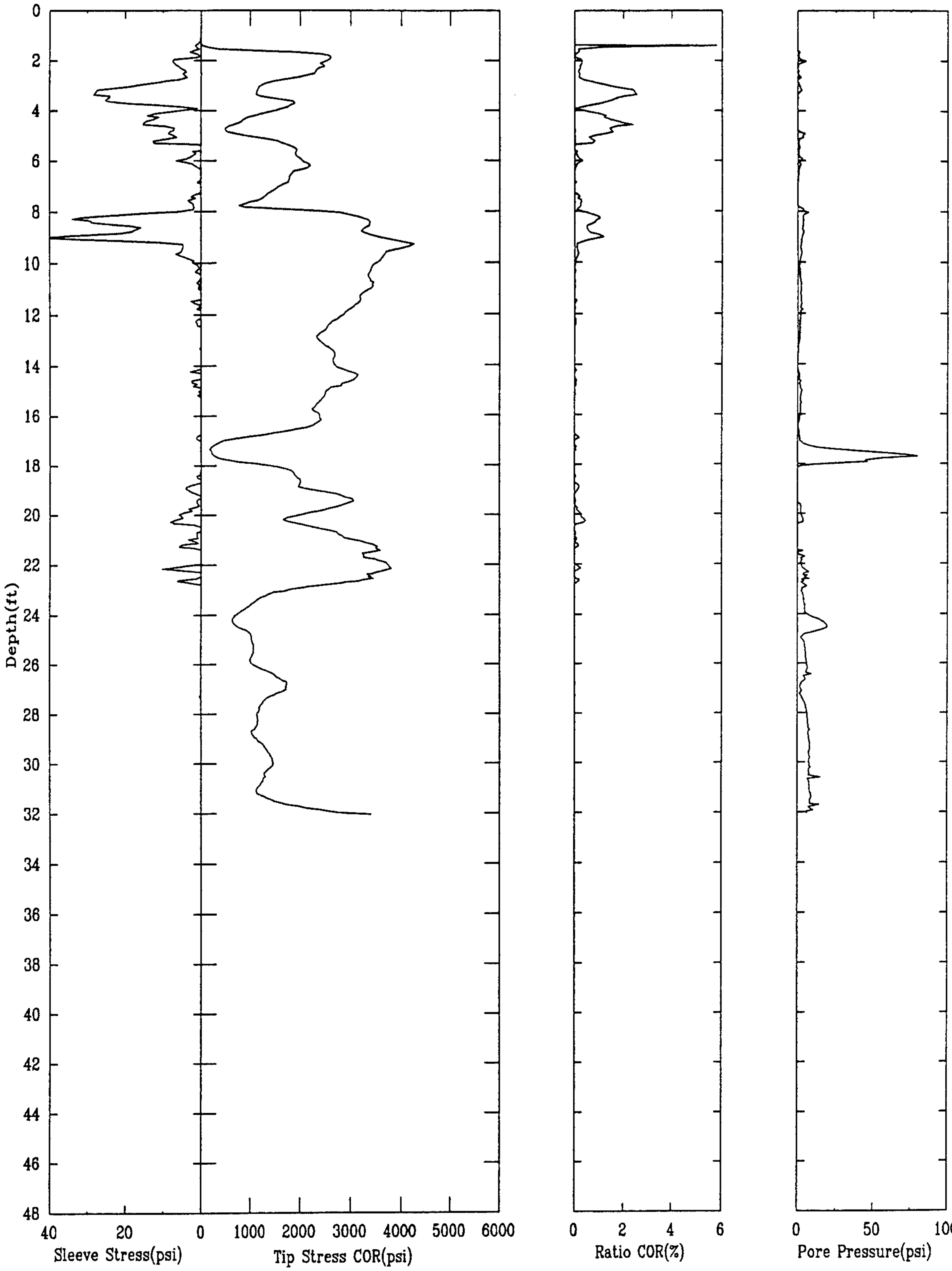
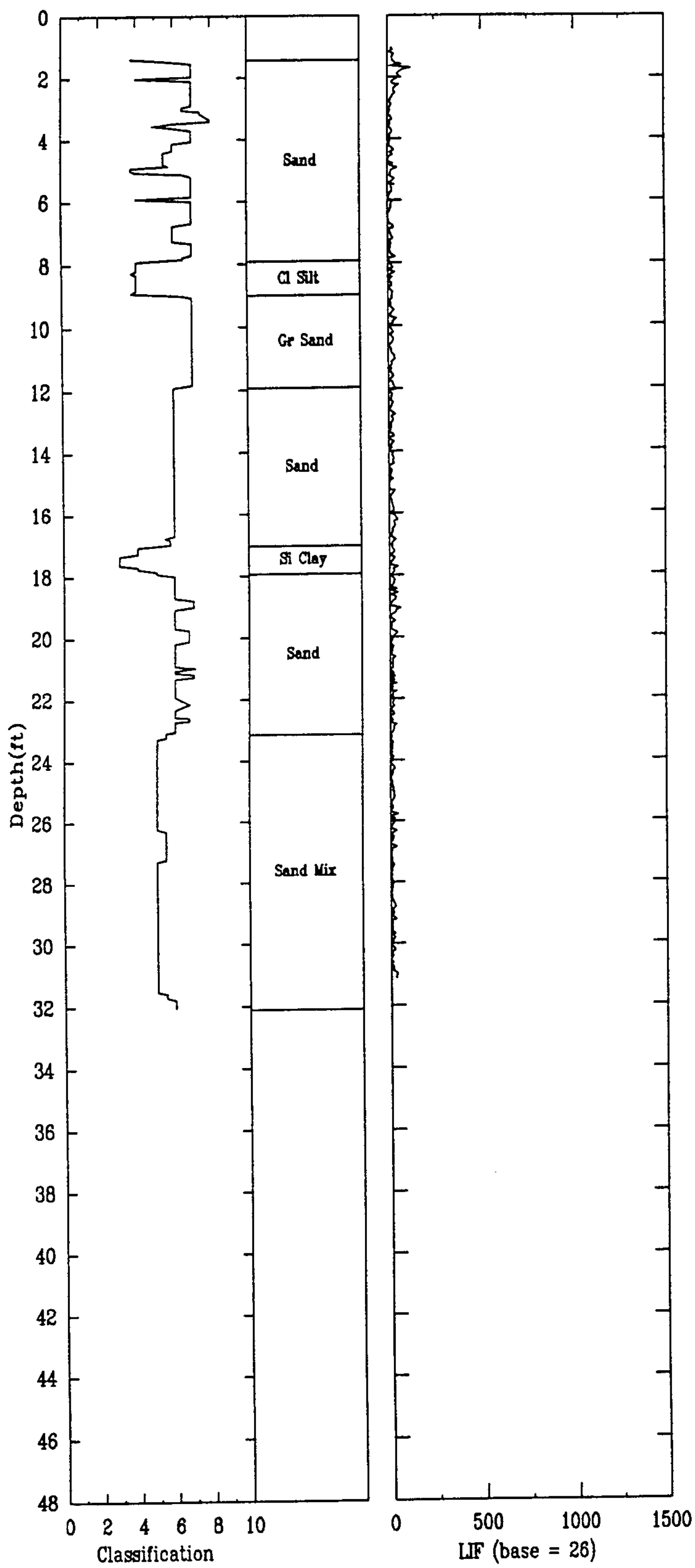
Dover Air Force Base

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8
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14
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22
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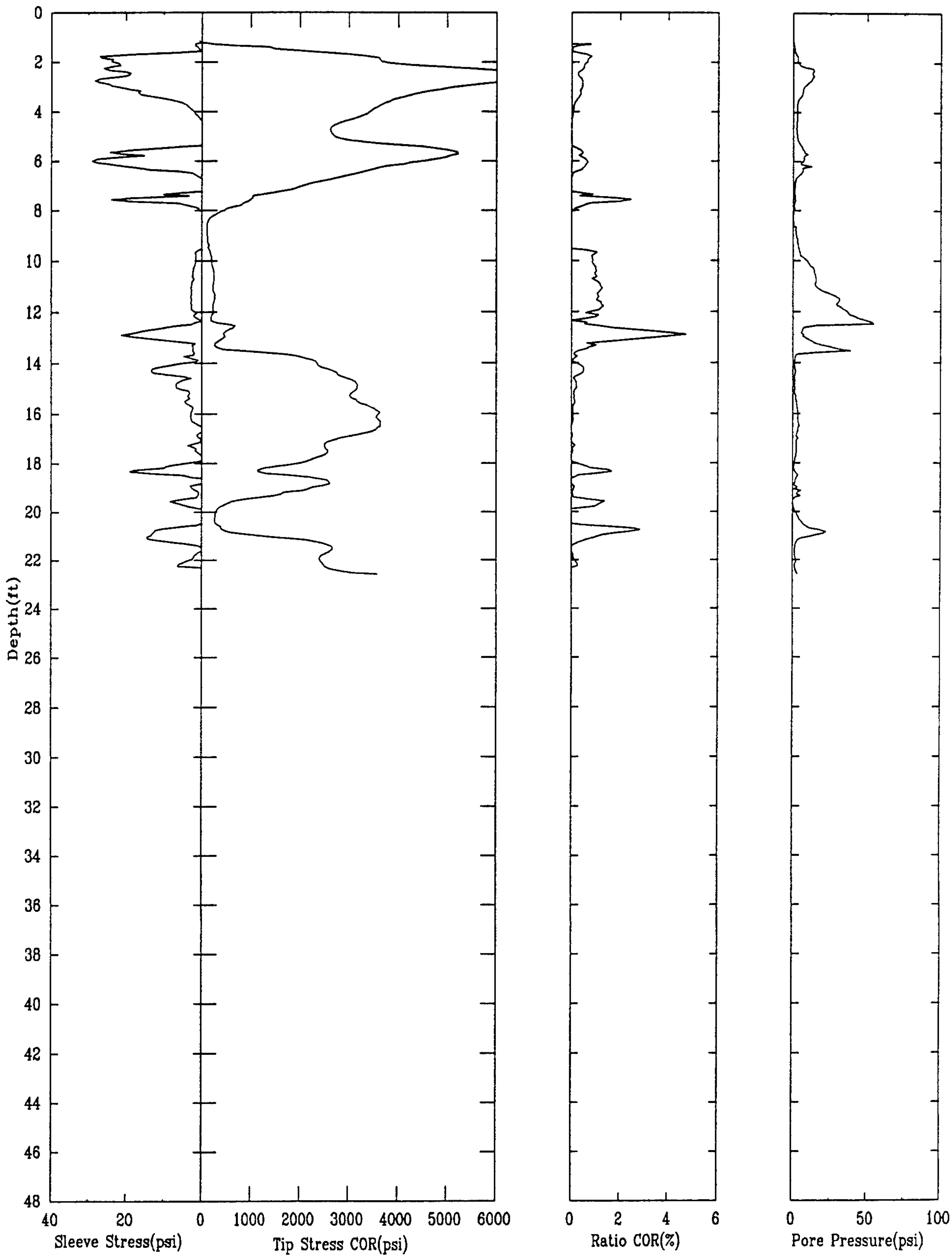
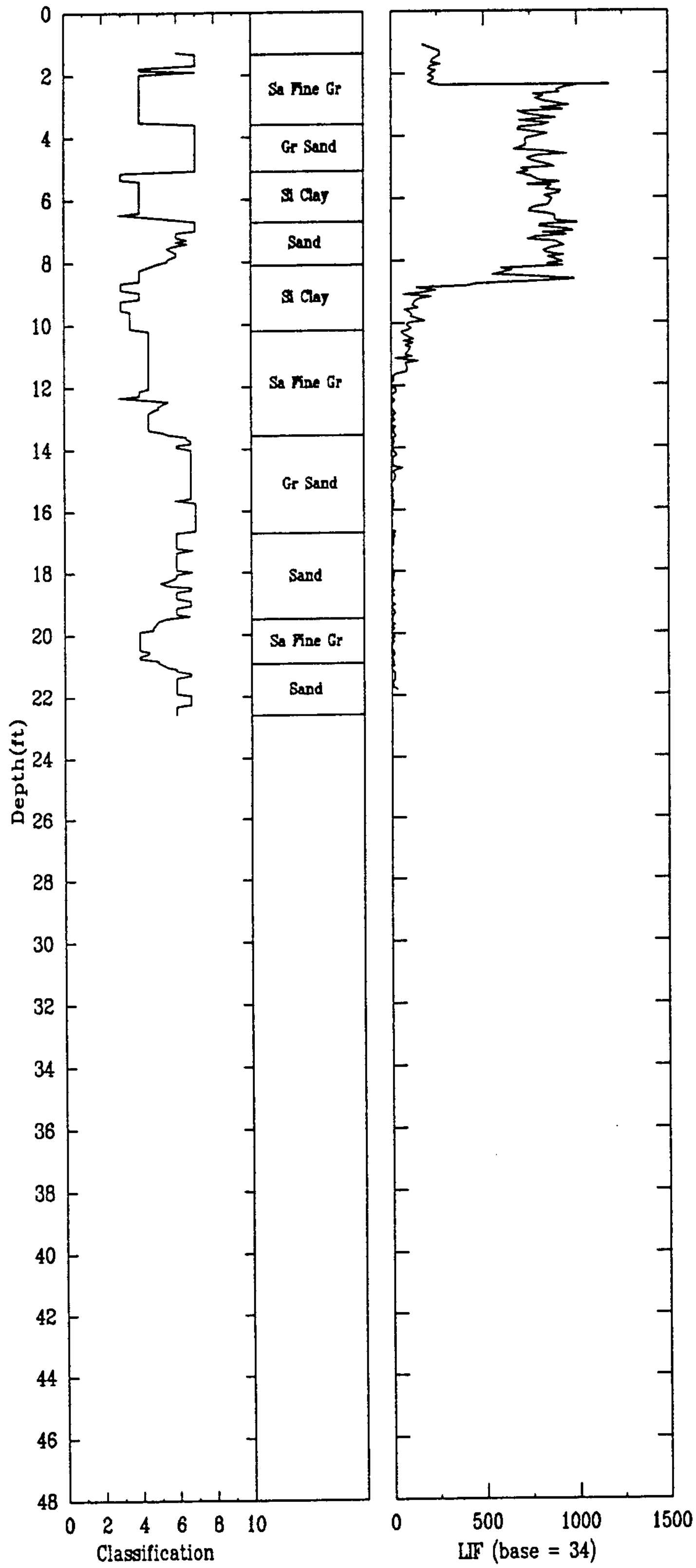
26
28
30
32
34
36
38
40
42
44
46
48
Sand
Cl Silt
Gr Sand
Sand
Si Clay
Sand
Sand Mix
0 2 4 6 8 10
Classification
0 500 1000 1500
LIF (base = 26)


Depth(ft)
Sleeve Stress(psi)
Tip Stress COR(psi)
Ratio COR(%)
Pore Pressure(psi)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12
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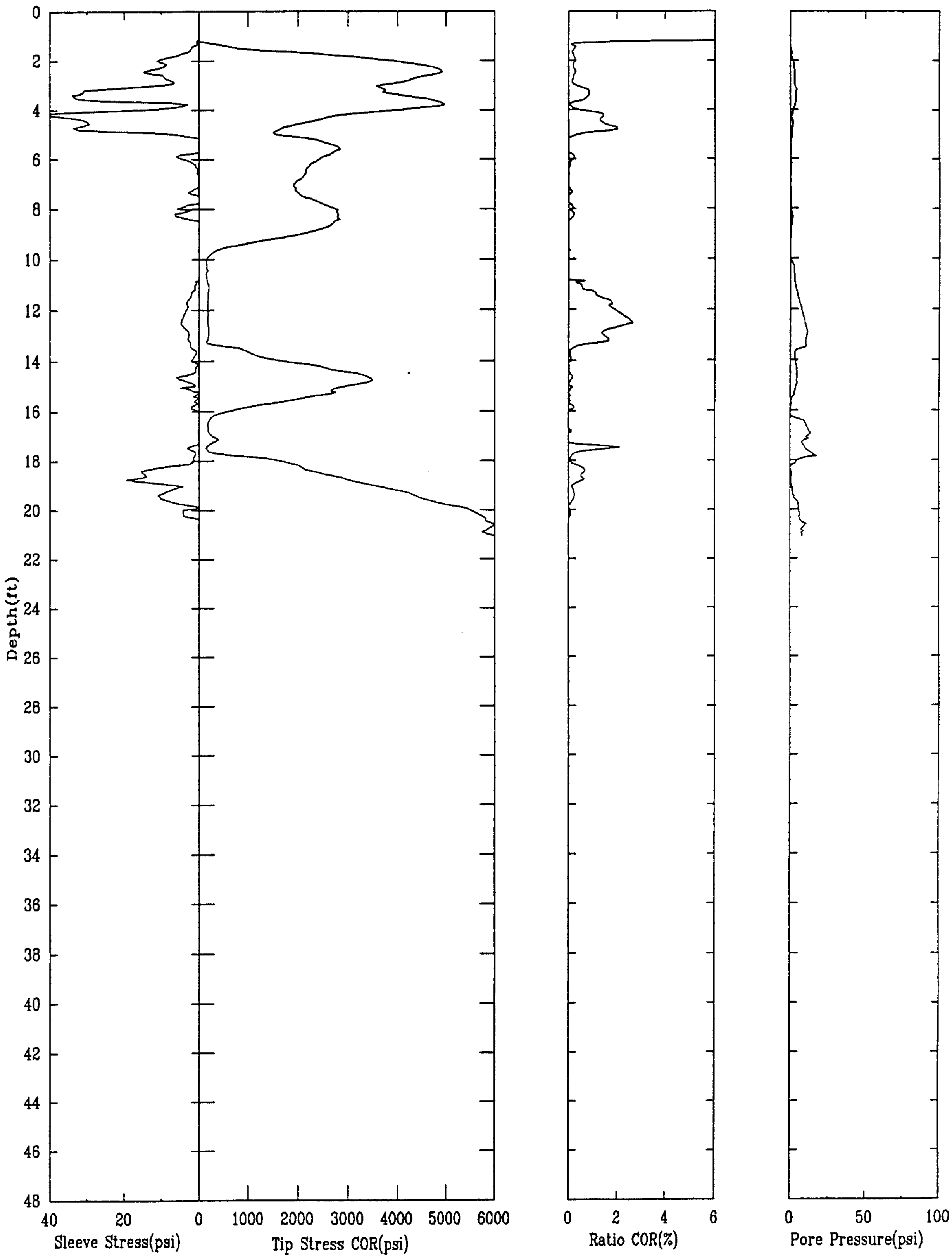
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
Depth(ft)
Sa Fine Gr
Gr Sand
Si Clay
Sand
Si Clay
Sa Fine Gr
Gr Sand
Sand
Sa Fine Gr
Sand
0 2 4 6 8 10
Classification
0 500 1000 1500
LIF (base = 34)

XYZ-CPT-05-LIF APPLIED RESEARCH ASSOCIATES, INC. 04/12/94

Dover Air Force Base



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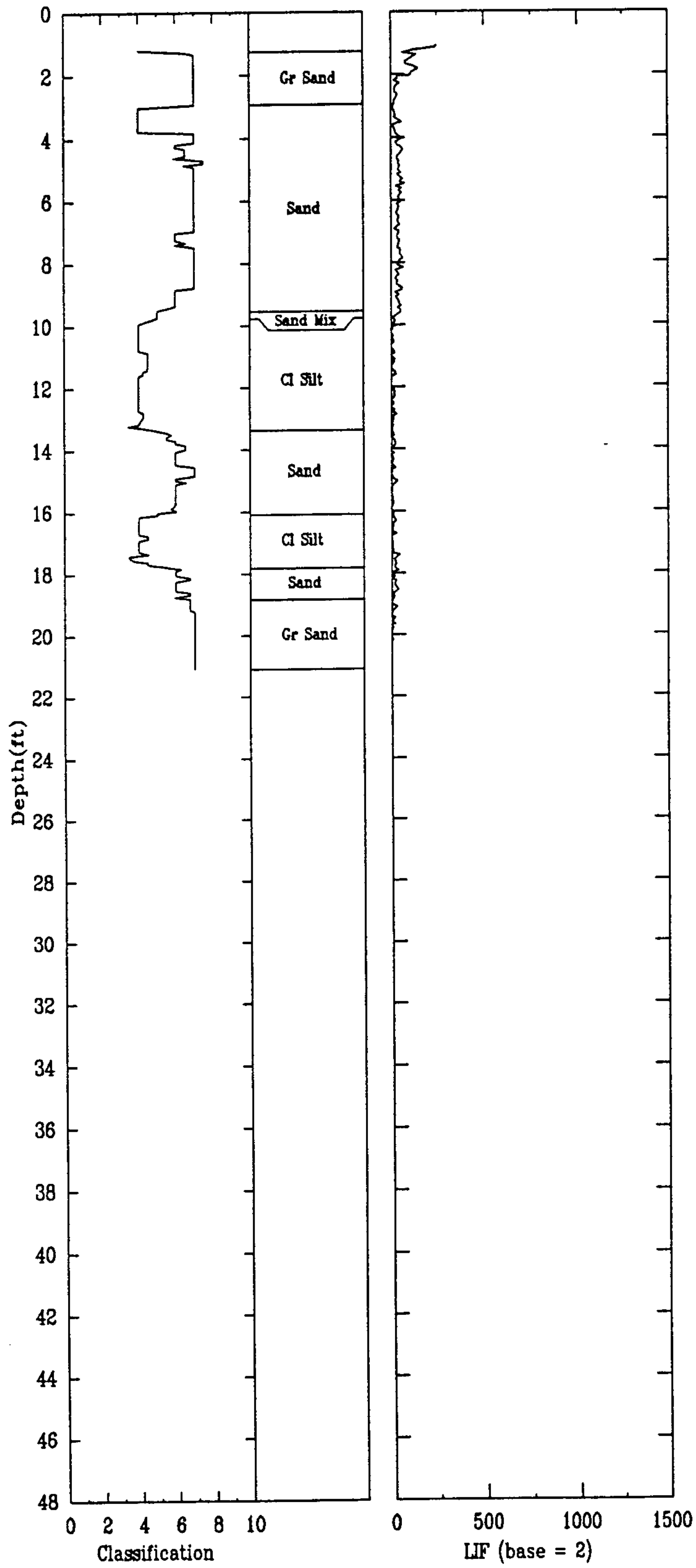
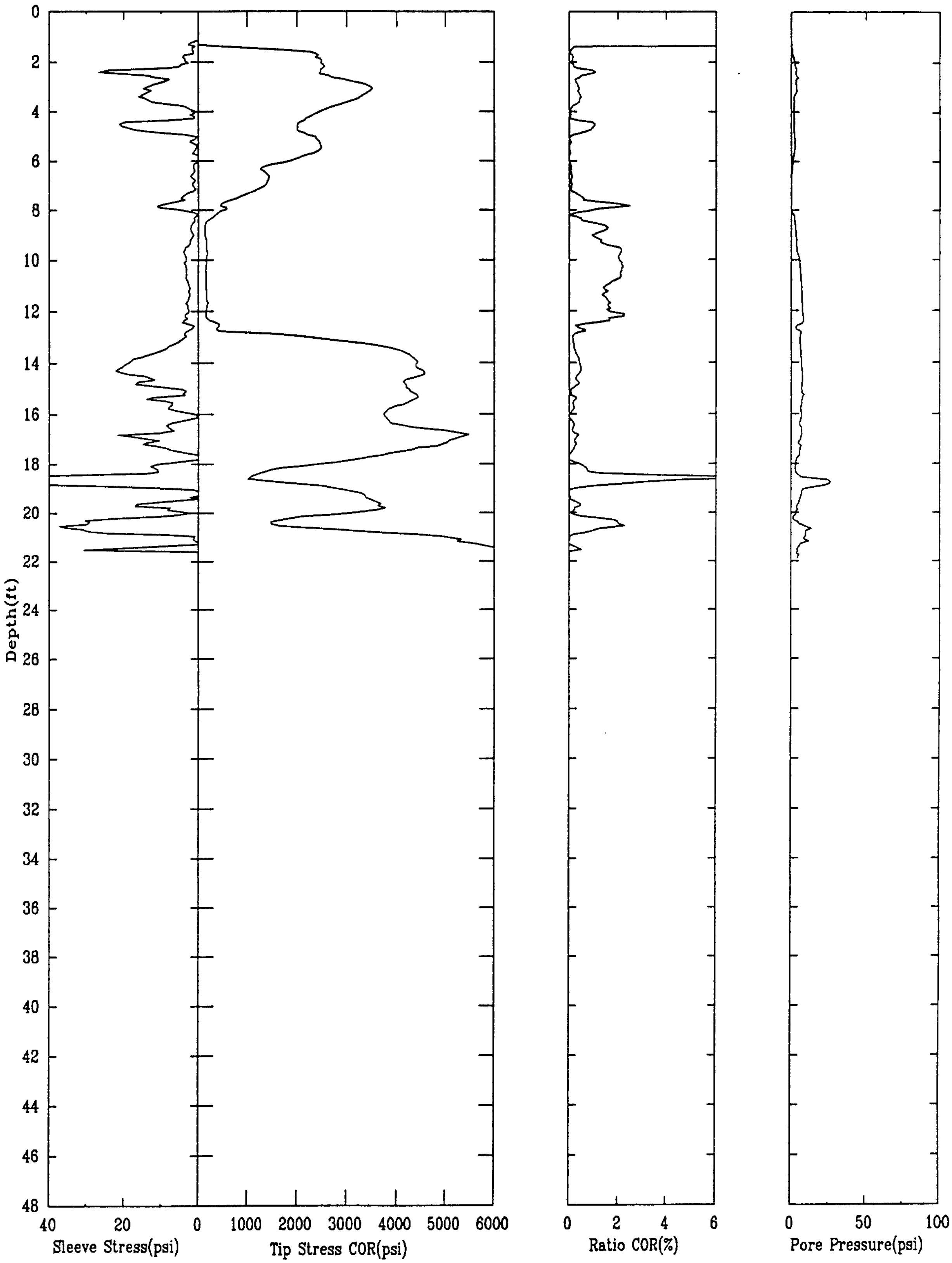
Dover Air Force Base

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18
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26
28
30
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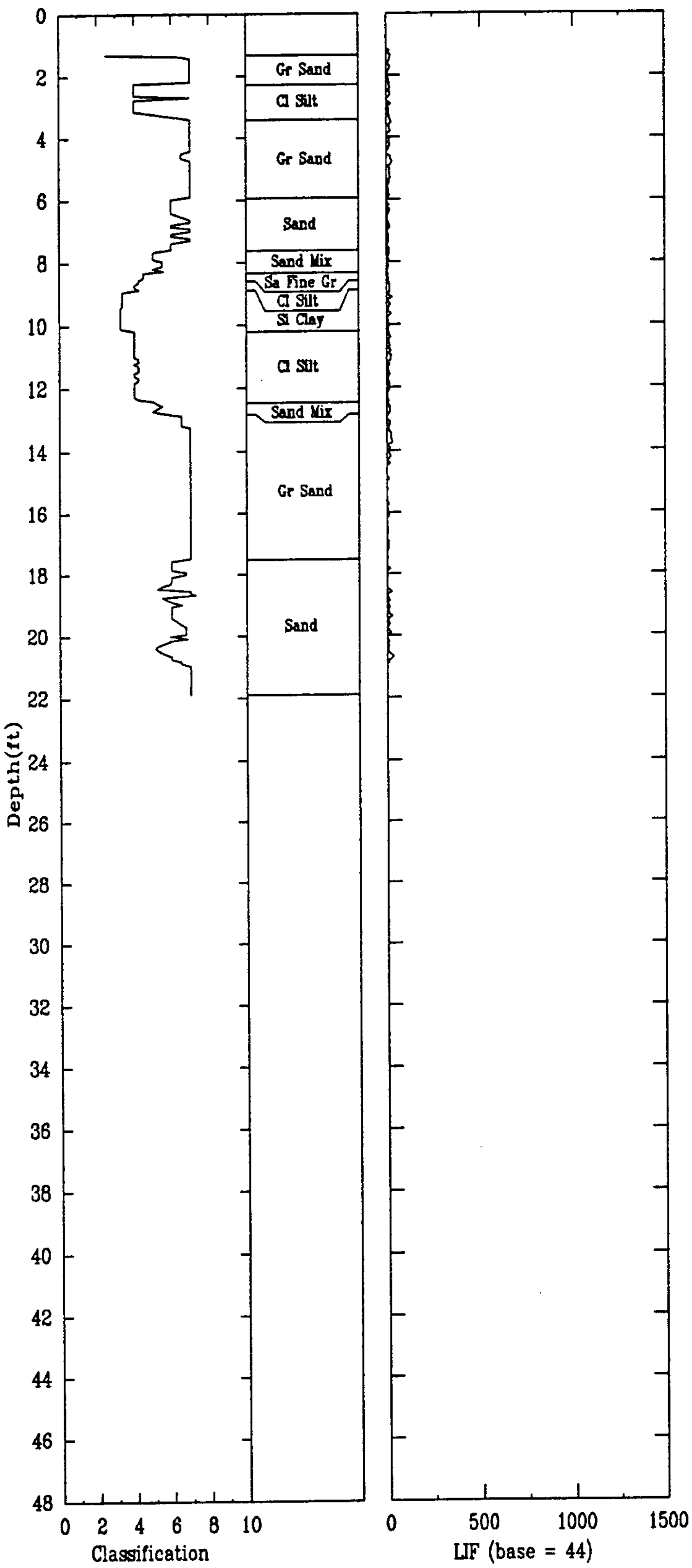
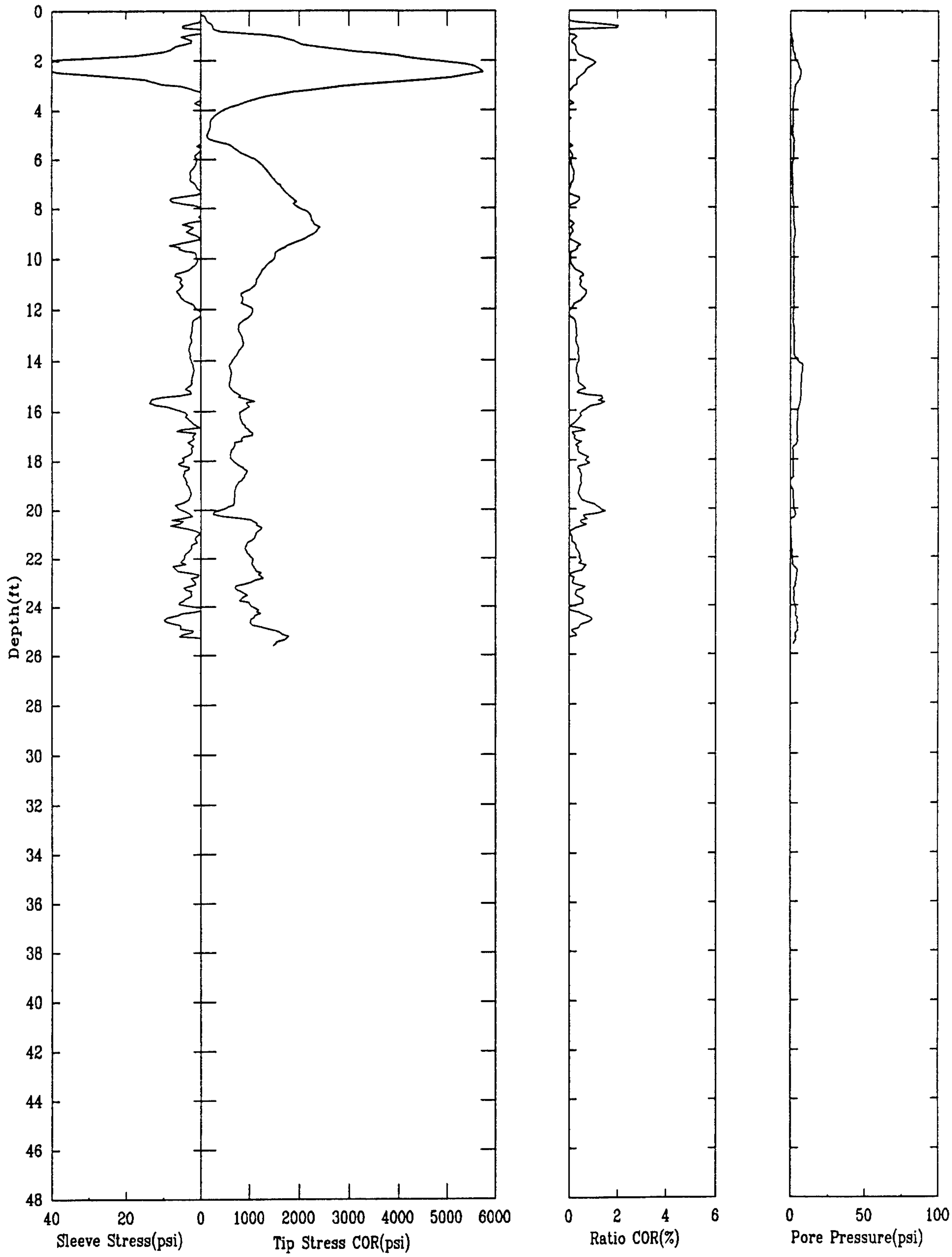
34
36
38
40
42
44
46
48
40
20
0
Sleeve Stress(psi)
0
1000
2000
3000
4000
5000
6000
Tip Stress COR(psi)
0
2
4
6
Ratio COR(%)
0
50
100
Pore Pressure(psi)

Dover Air Force Base

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20
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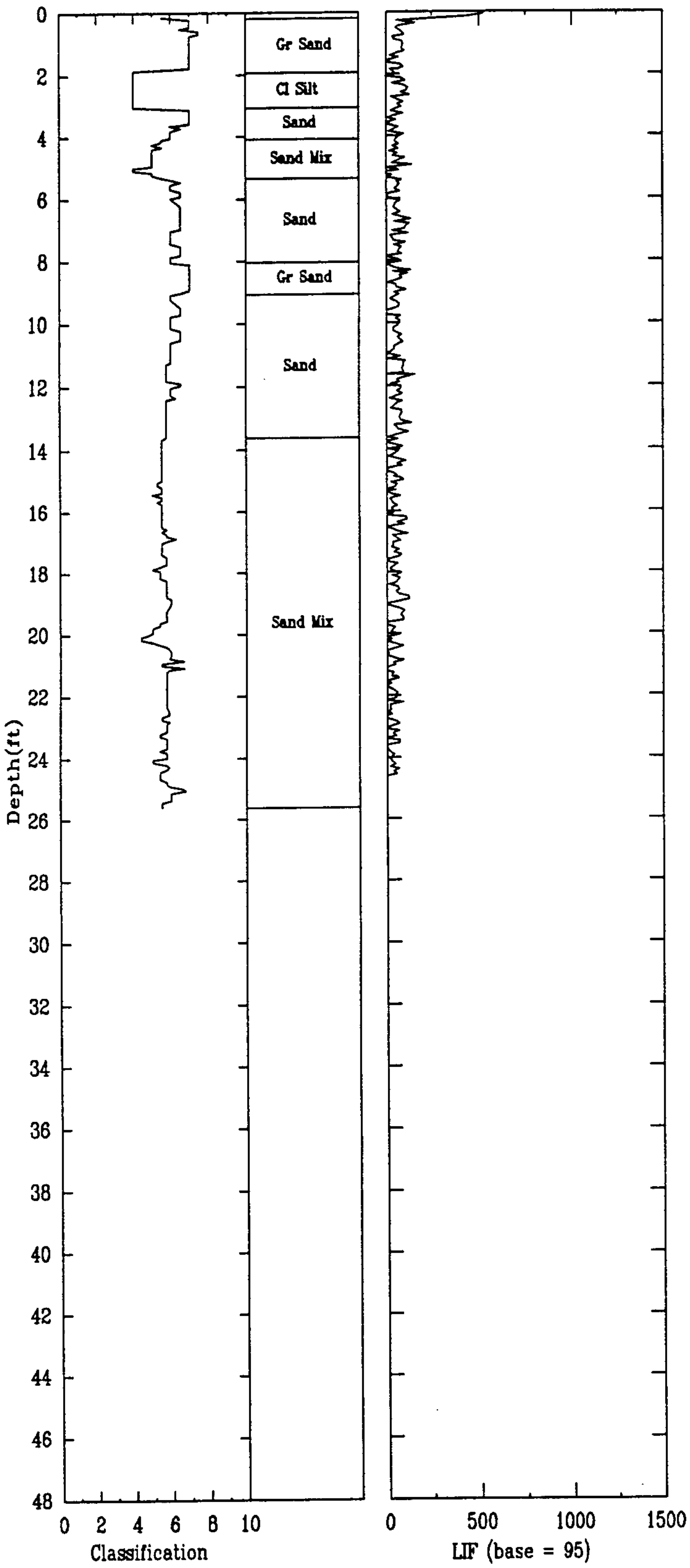
36
38
40
42
44
46
48
40
20
0
Sleeve Stress(psi)
0
1000
2000
3000
4000
5000
6000
Tip Stress COR(psi)
0
2
4
6
Ratio COR(%)
0
50
100
Pore Pressure(psi)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18
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30
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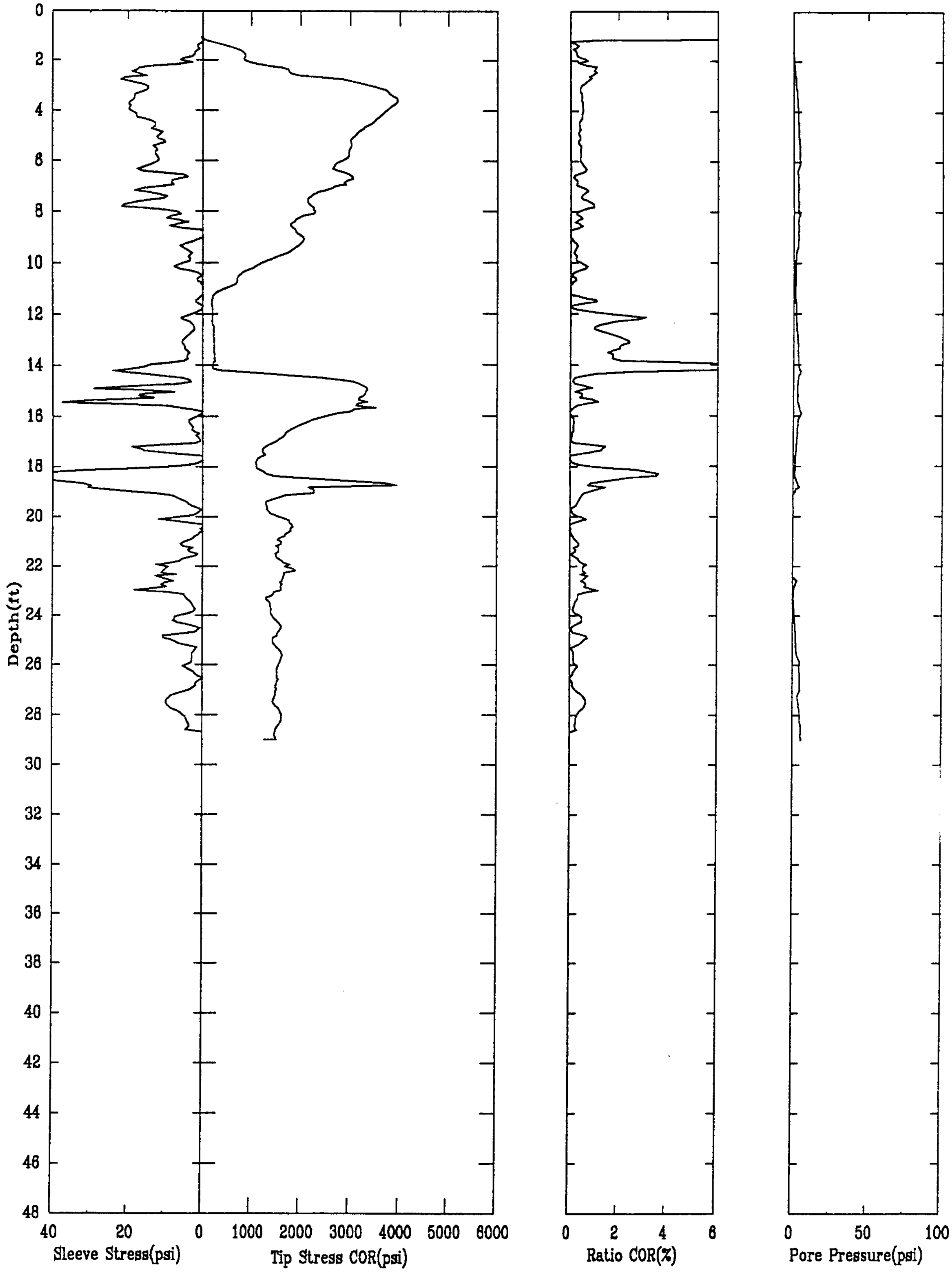
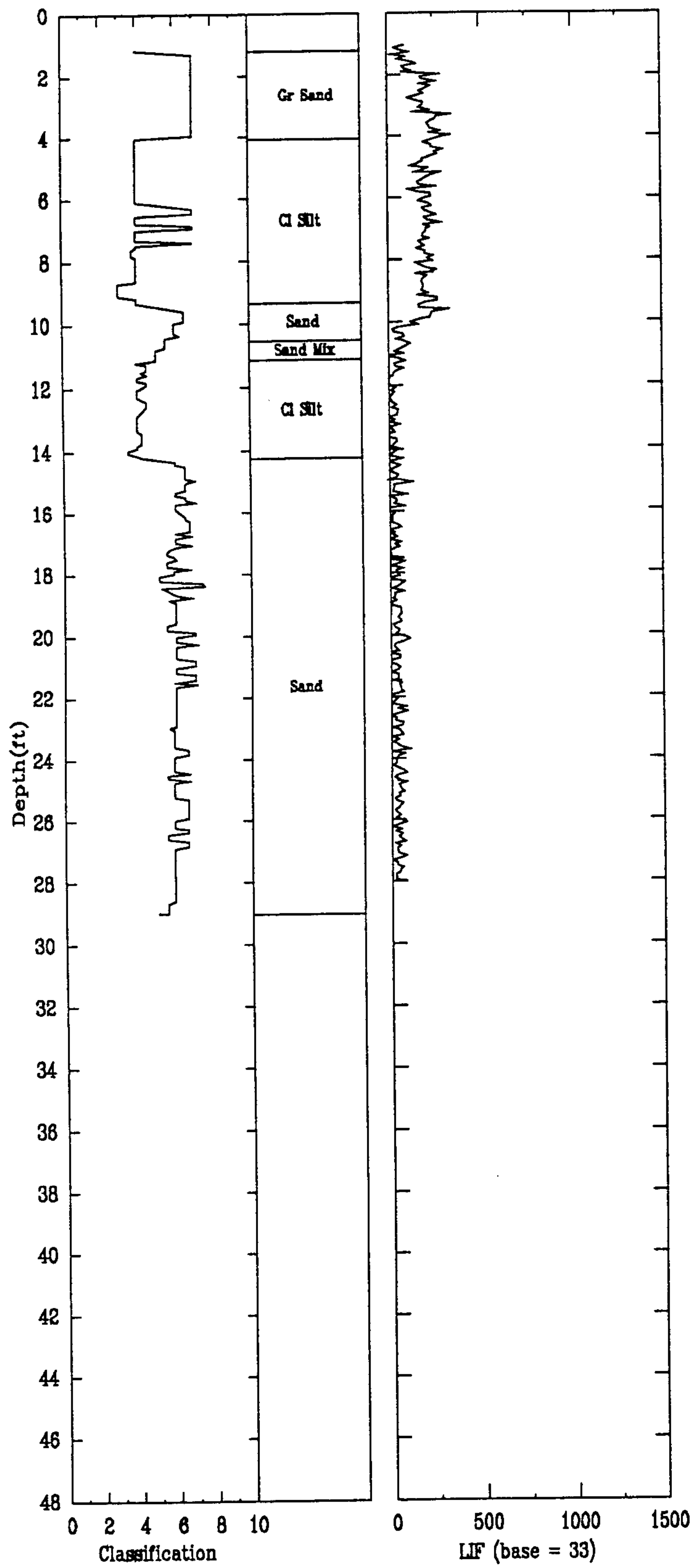
34
36
38
40
42
44
46
48
Gr Sand
Cl Silt
Sand
Sand Mix
Sand
Gr Sand
Sand
Sand Mix
0 2 4 6 8 10
Classification
0 500 1000 1500
LIF (base = 95)

XYZ-CPT-08-LIF APPLIED RESEARCH ASSOCIATES, INC. 04/13/94

Dover Air Force Base




Depth(ft)
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18
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22
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30
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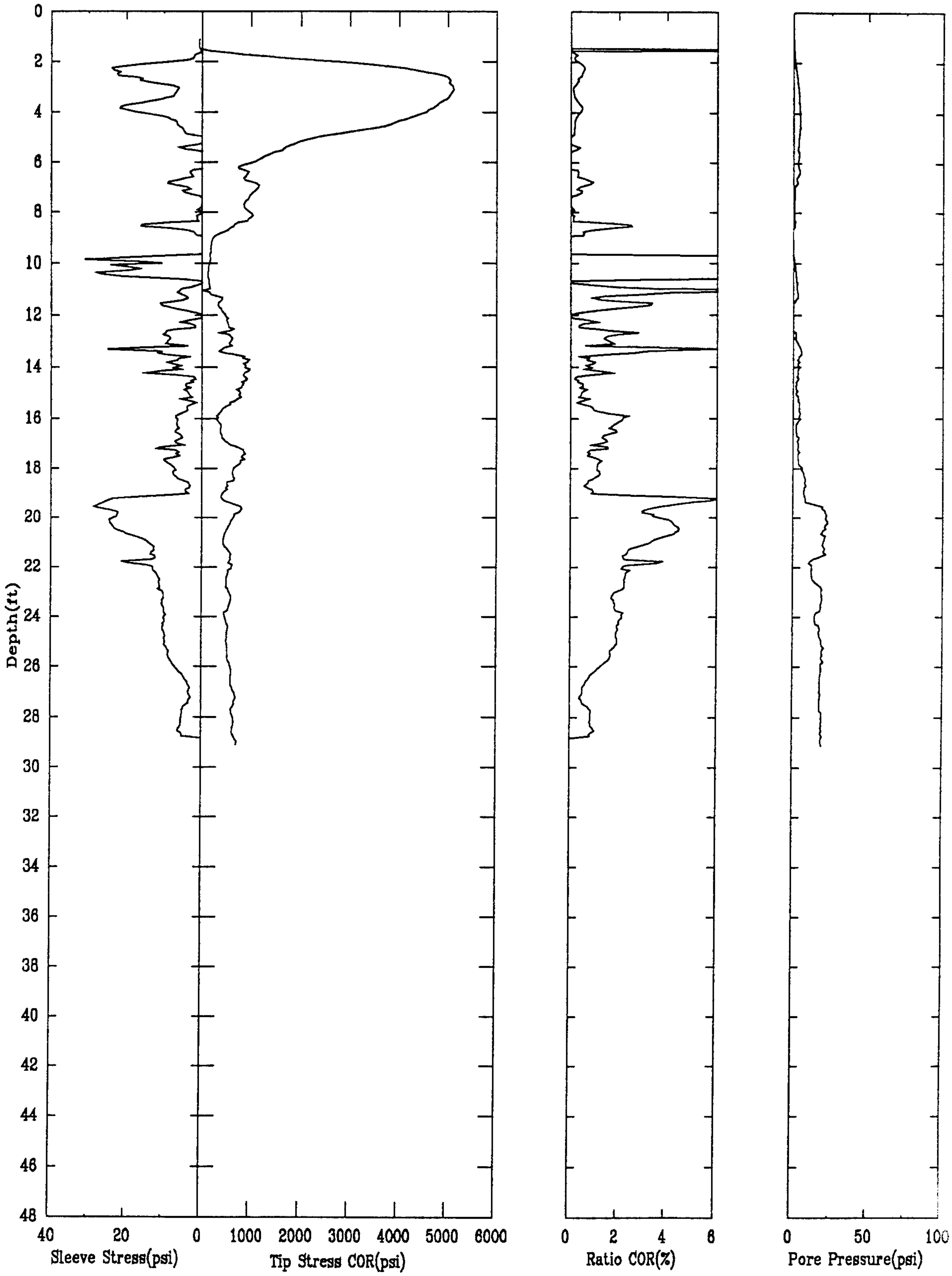
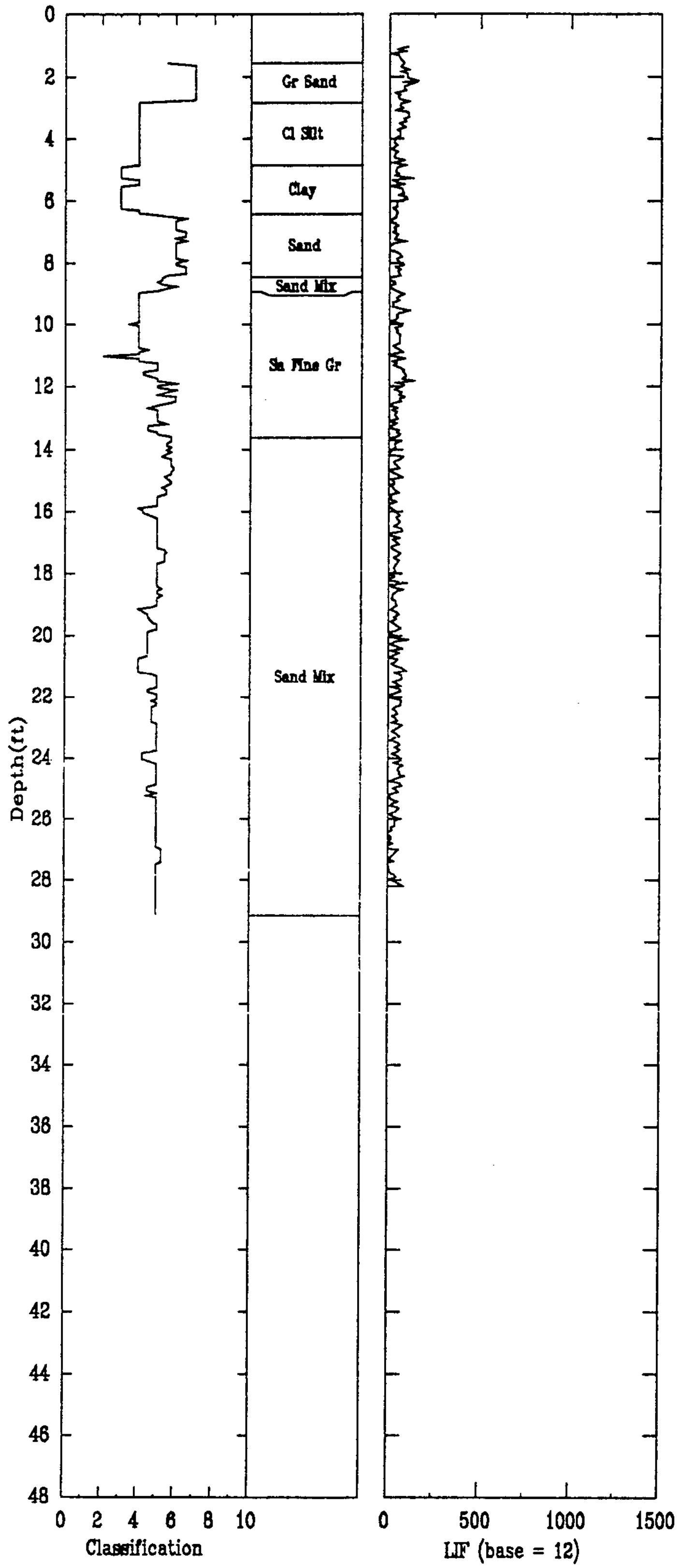
34
36
38
40
42
44
46
48
Gr Sand
Cl Silt
Sand
Sand Mix
Cl Silt
Sand
0 2 4 6 8 10
Classification
0 500 1000 1500
LIF (base = 33)

XYZ-CPT-09-LIF APPLIED RESEARCH ASSOCIATES, INC. 04/13/94

Dover Air Force Base

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12
14
16
18
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22
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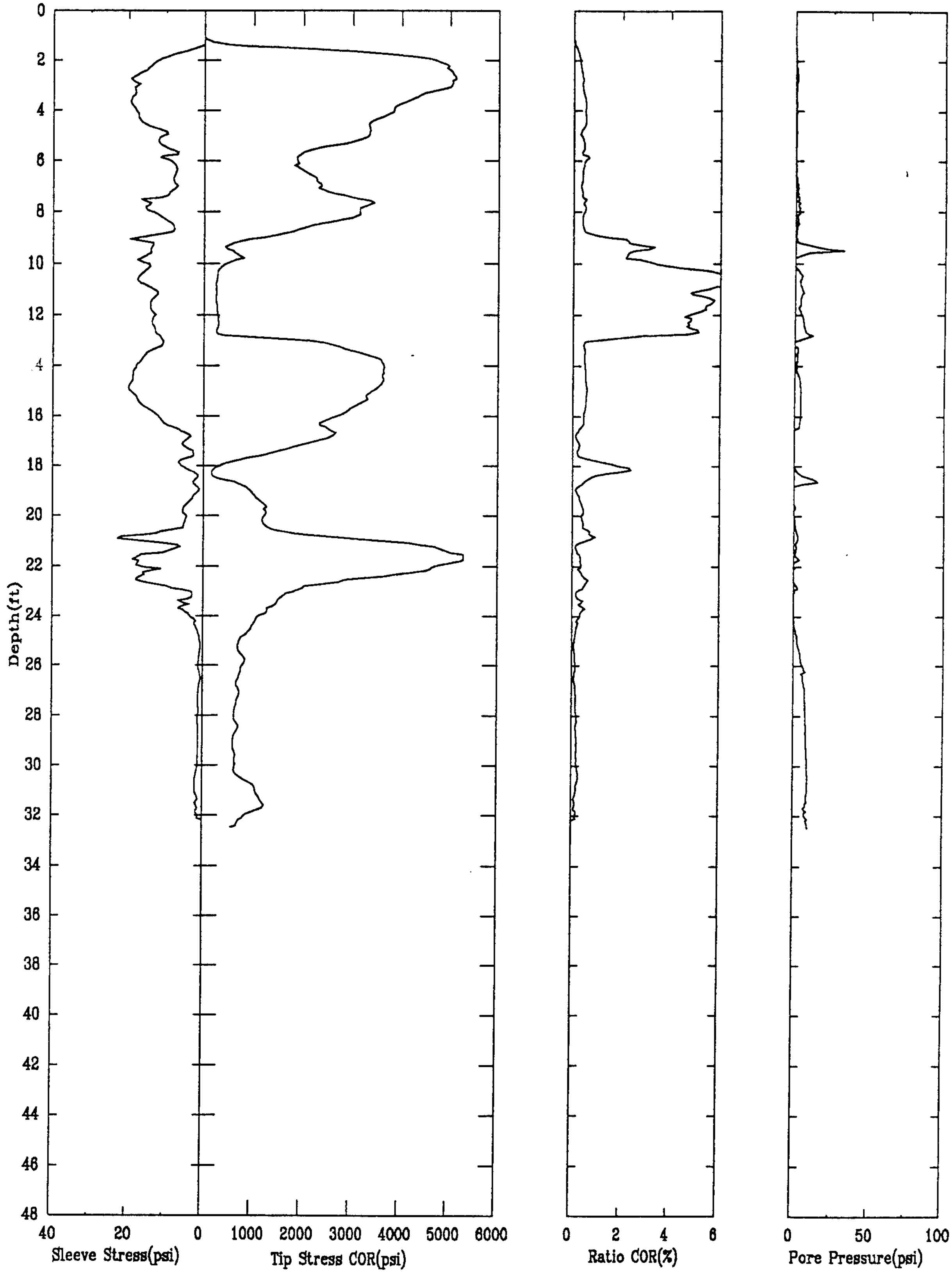
36
38
40
42
44
46
48
Gr Sand
Cl Silt
Clay
Sand
Sand Mix
Sa Fine Gr
Sand Mix
0 2 4 6 8 10
Classification
0 500 1000 1500
LIF (base = 12)

XYZ-CPT-10-LIF APPLIED RESEARCH ASSOCIATES, INC. 04/13/94

Dover Air Force Base



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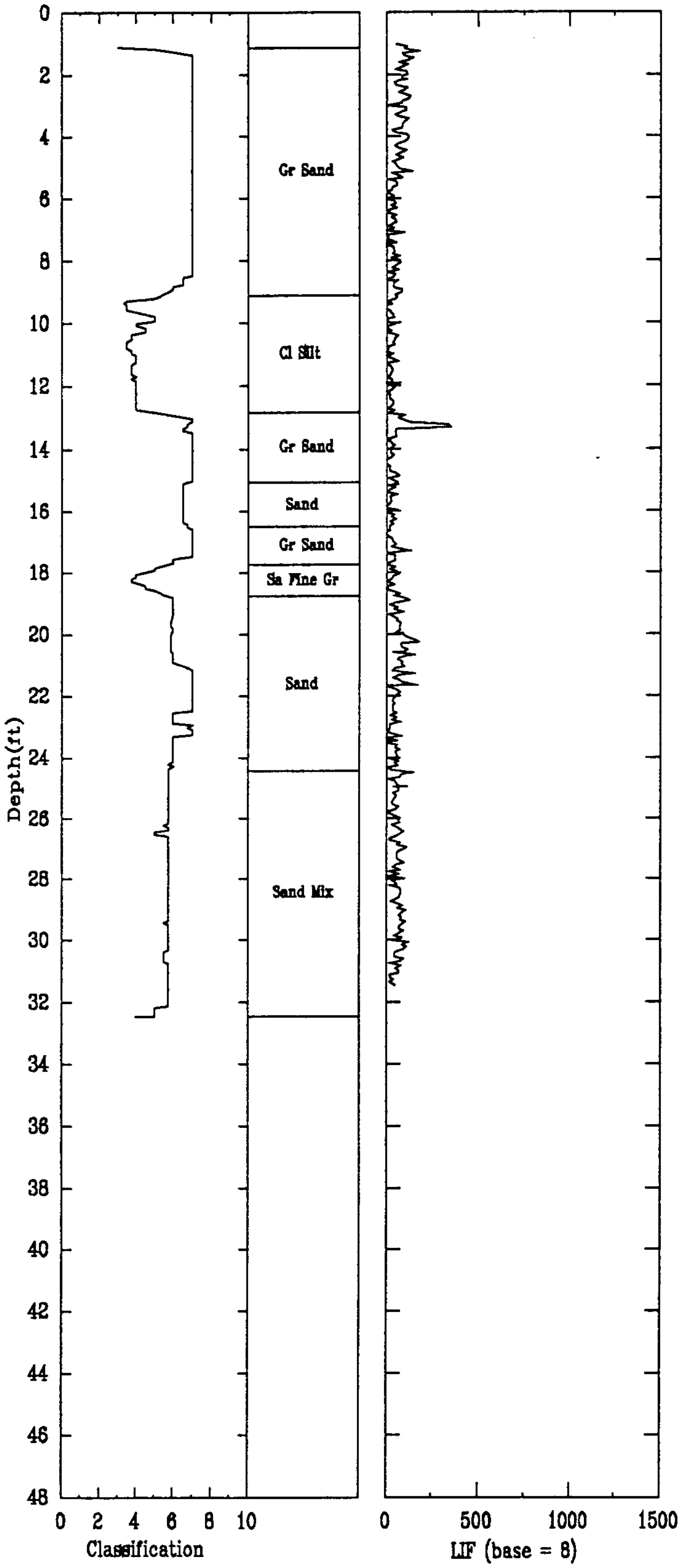

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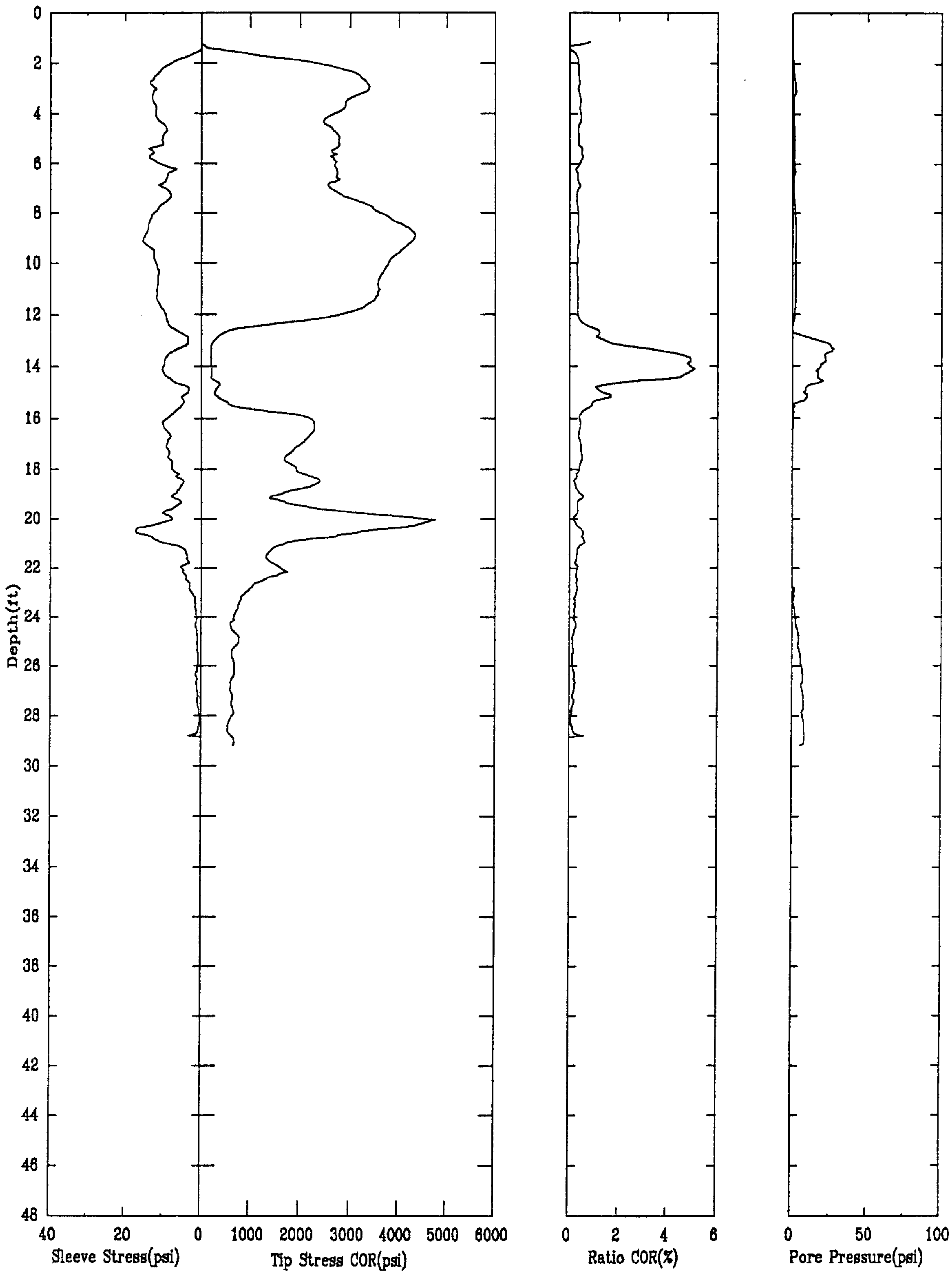

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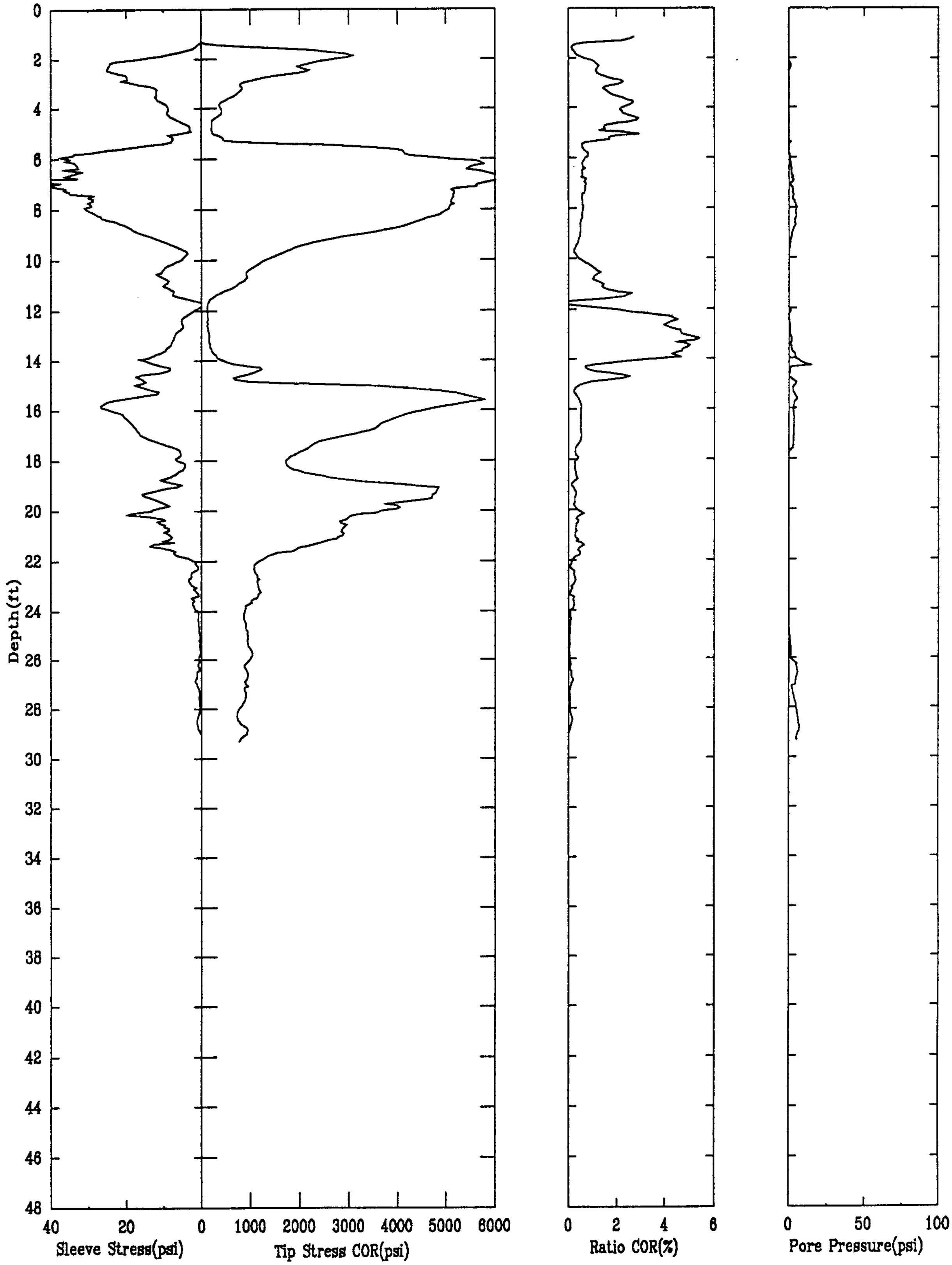

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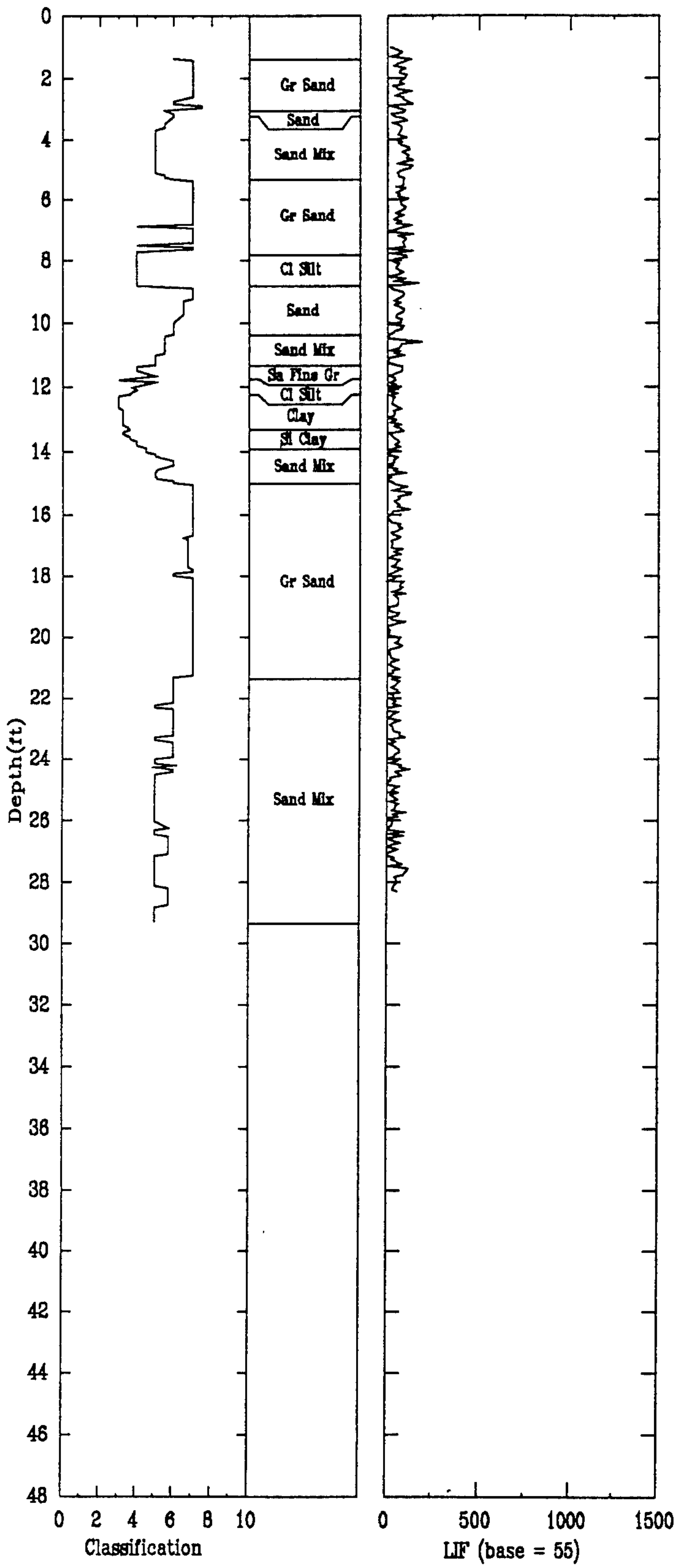

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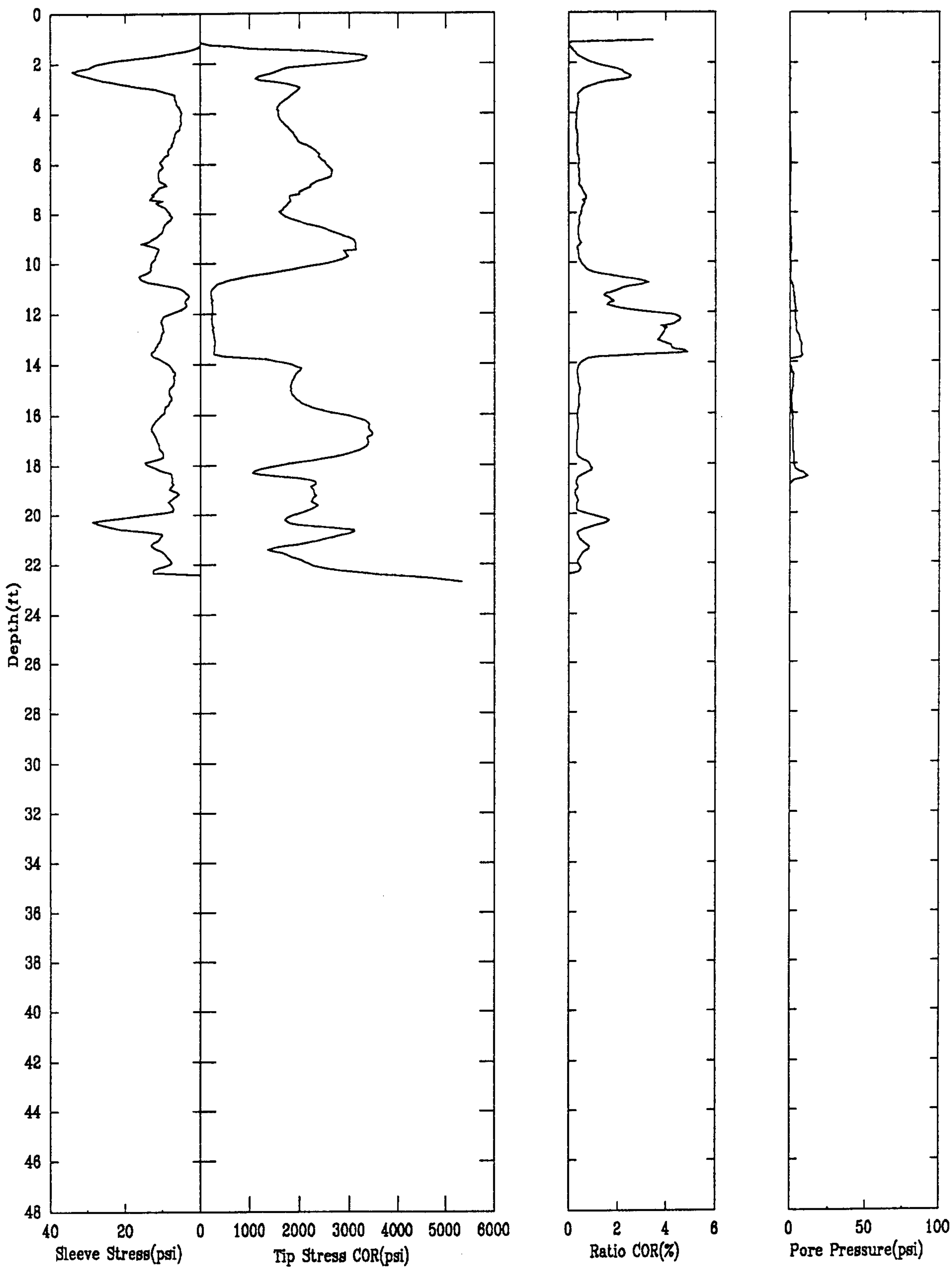
Dover Air Force Base



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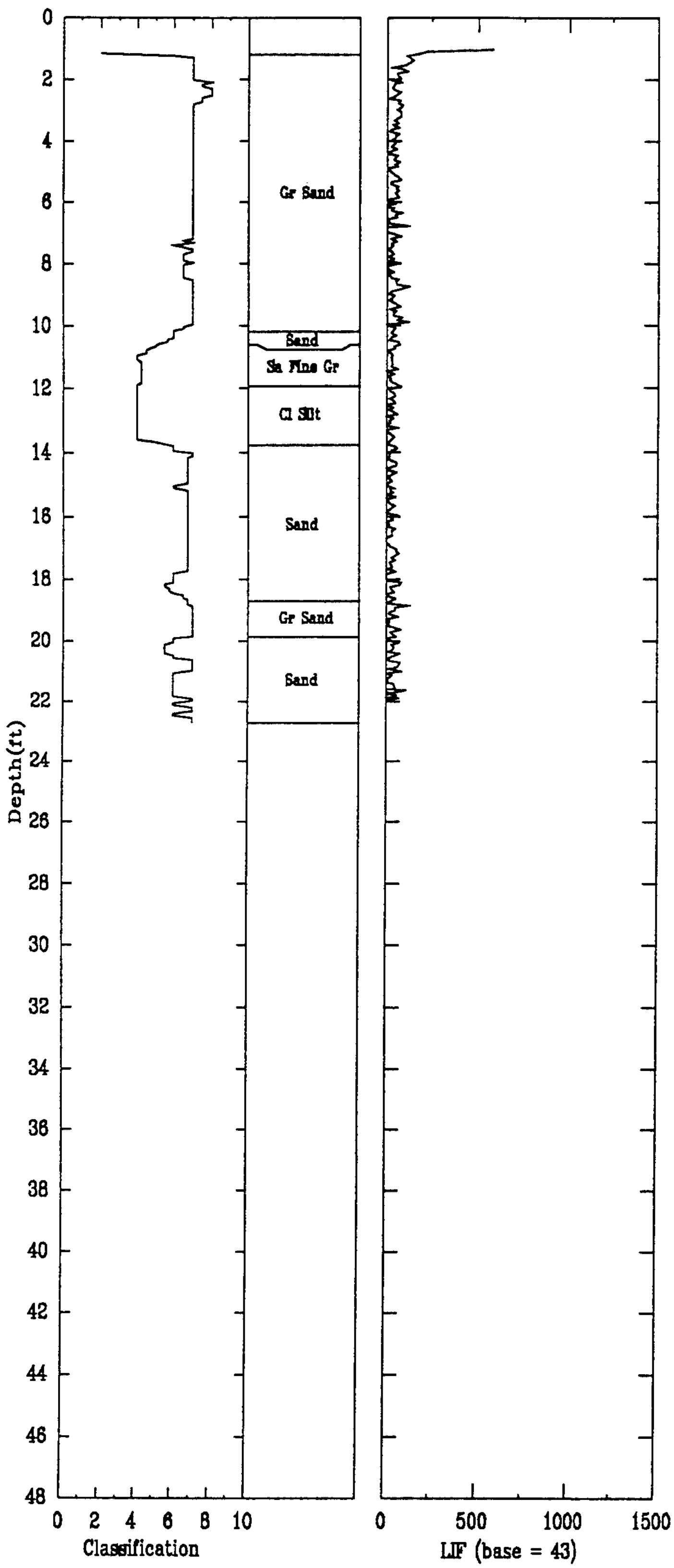
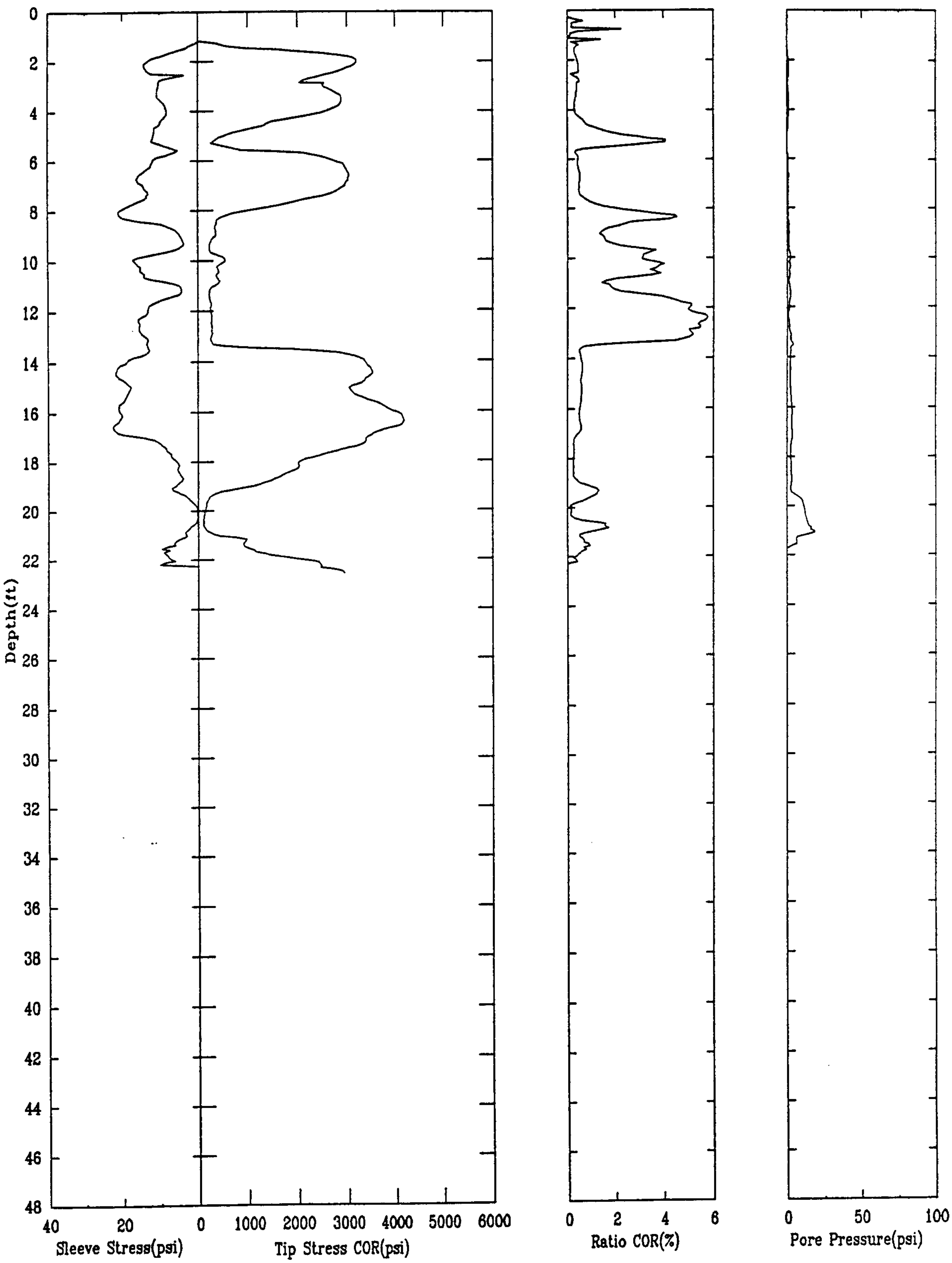
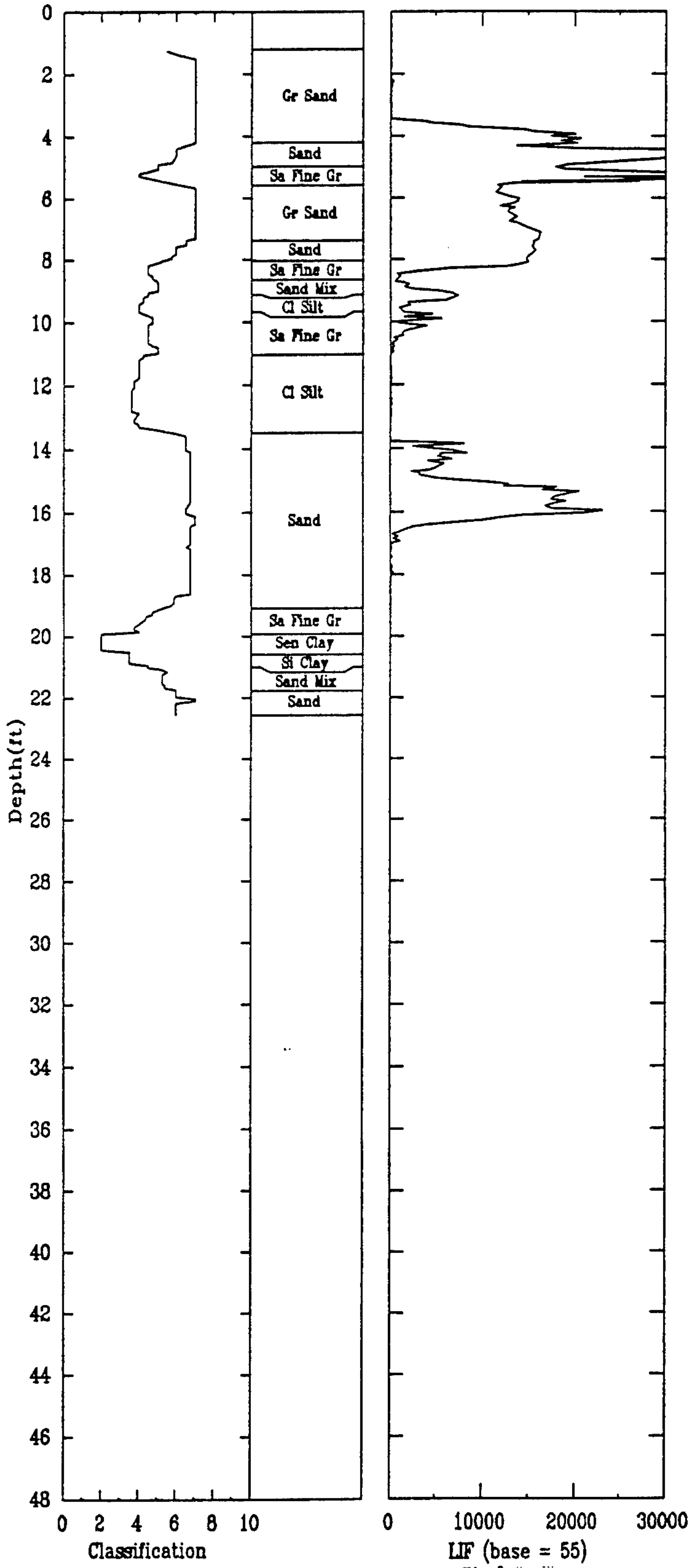
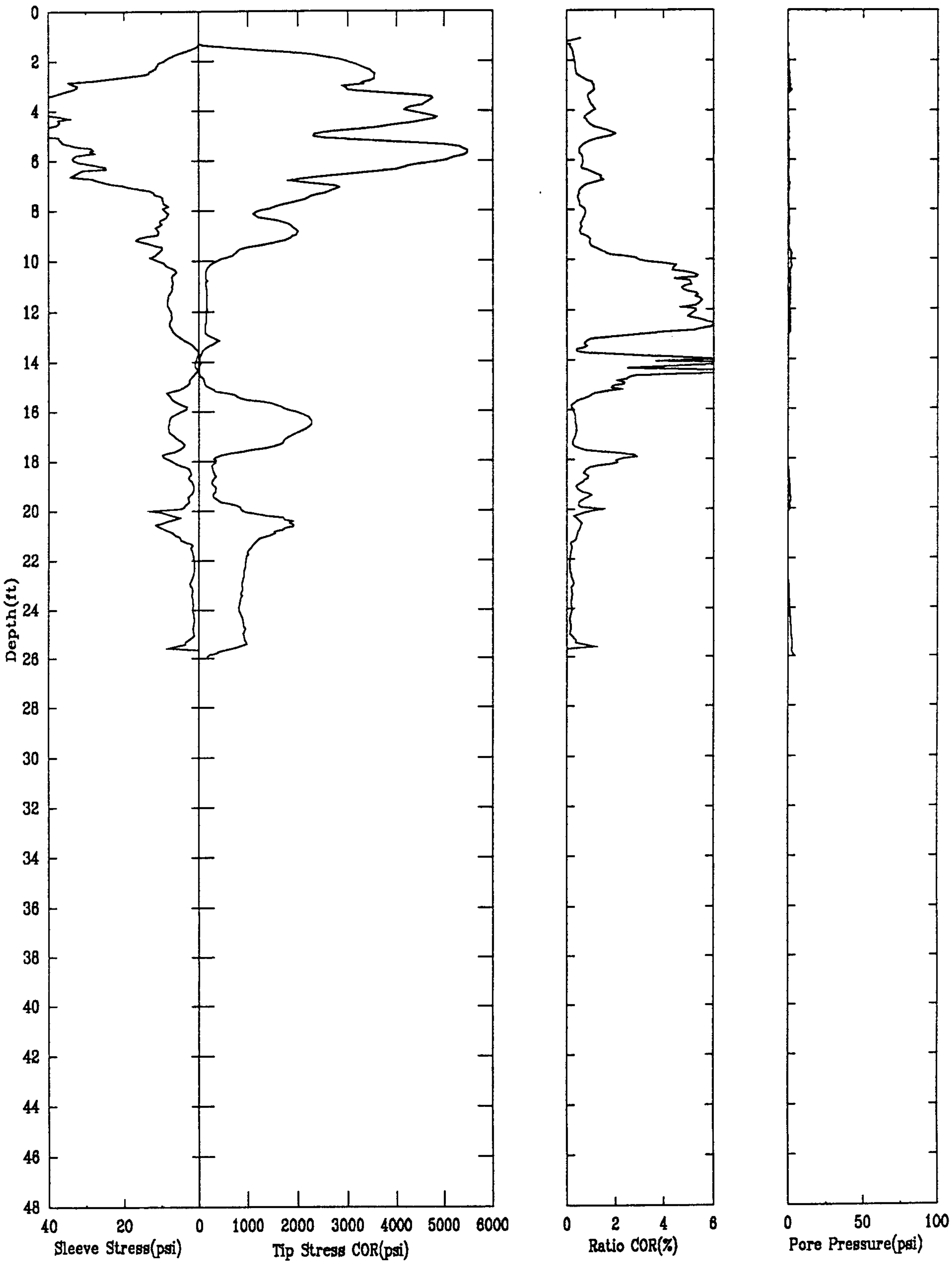


XYZ-CPT-14-LIF APPLIED RESEARCH ASSOCIATES, INC. 04/14/94

Dover Air Force Base




Gr Sand
Sand
Sa Fine Gr
Gr Sand
Sand
Sa Fine Gr
Sand Mix
Cl Silt
Sa Fine Gr
Cl Silt
Sand
Sa Fine Gr
Sen Clay
Si Clay
Sand Mix
Sand
Depth(ft)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
0 2 4 6 8 10
Classification
0 10000 20000 30000
LIF (base = 55)


Depth(ft)
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4
6
8
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12
14
16
18
20
22
24
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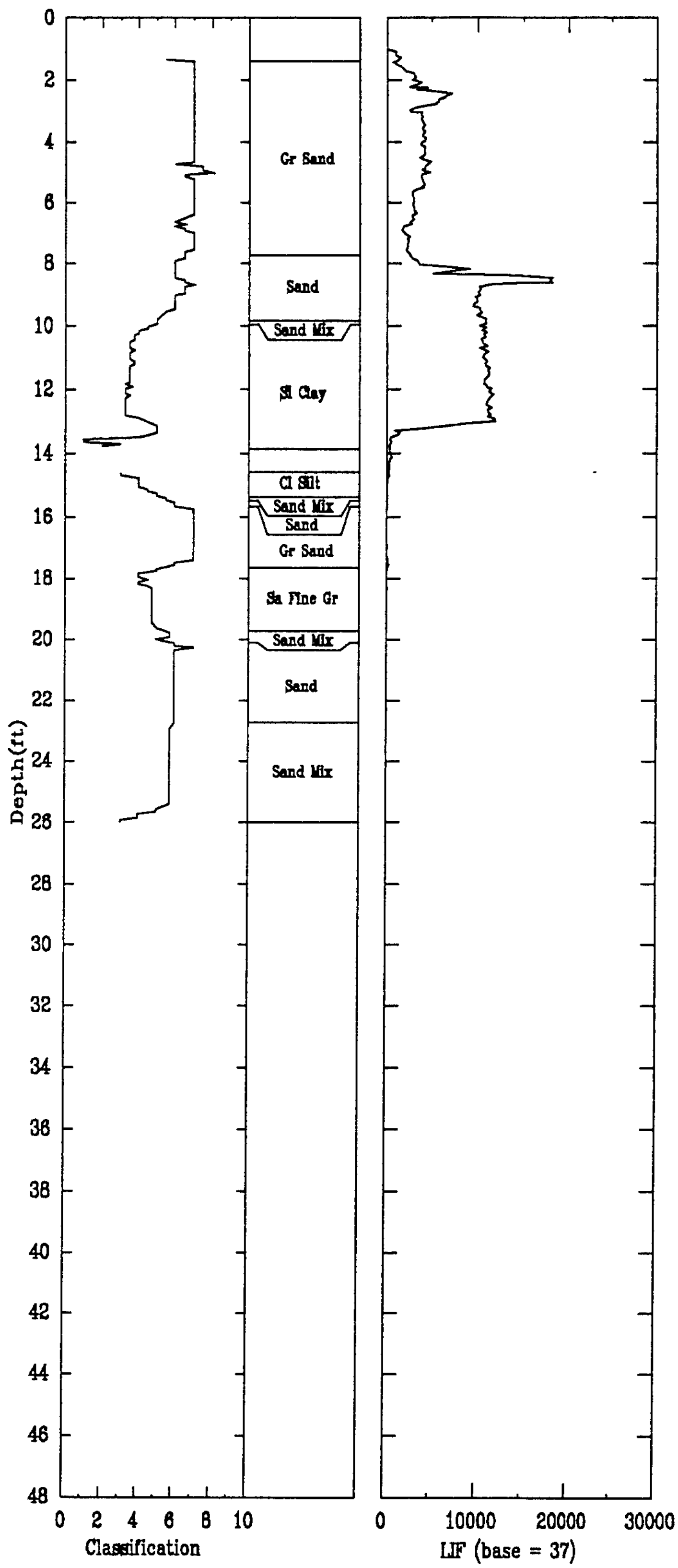
28
30
32
34
36
38
40
42
44
46
48
40
20
0
Sleeve Stress(psi)
0
1000
2000
3000
4000
5000
6000
Tip Stress COR(psi)
0
2
4
6
Ratio COR(%)
0
50
100
Pore Pressure(psi)

Dover Air Force Base



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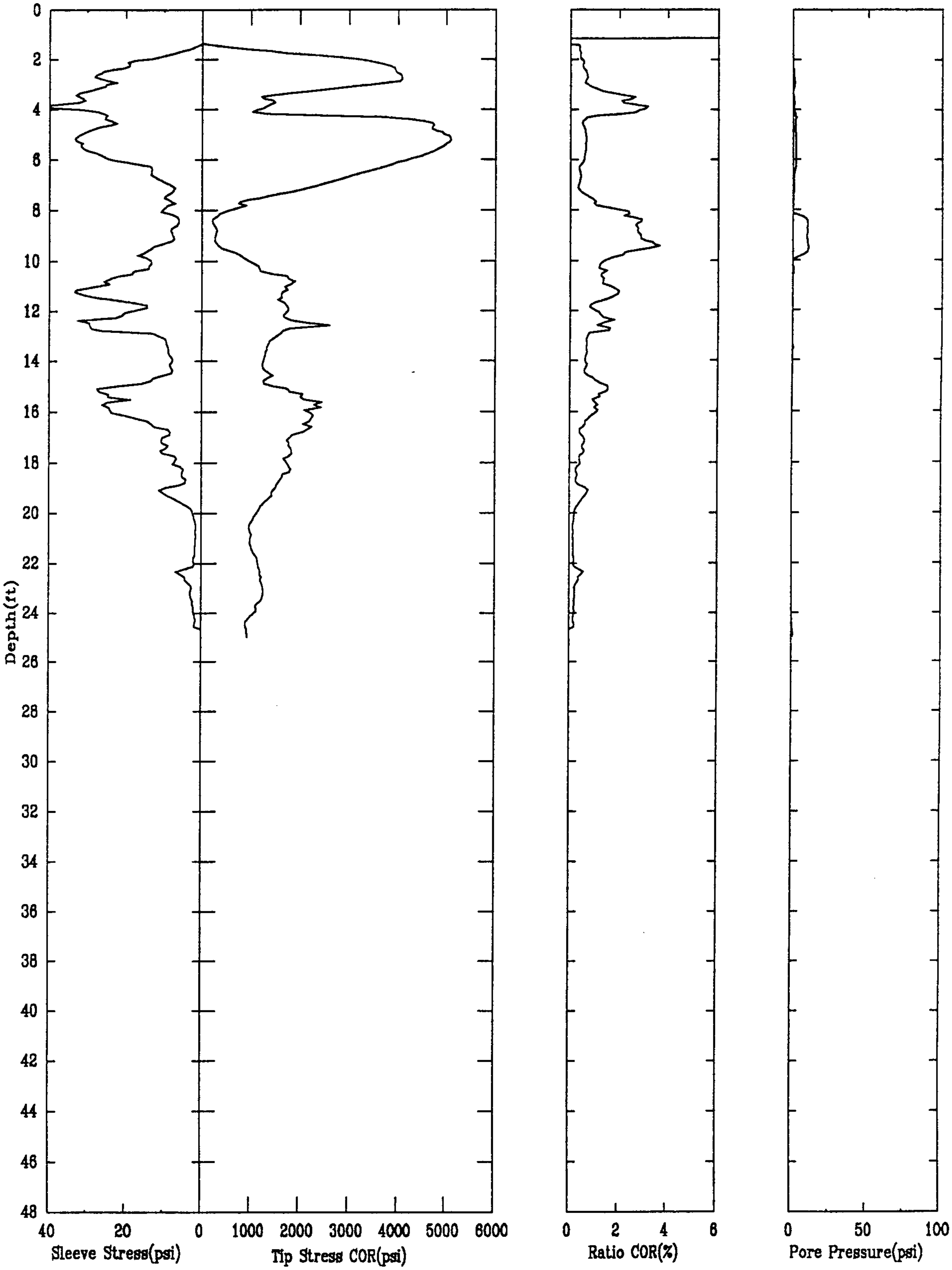
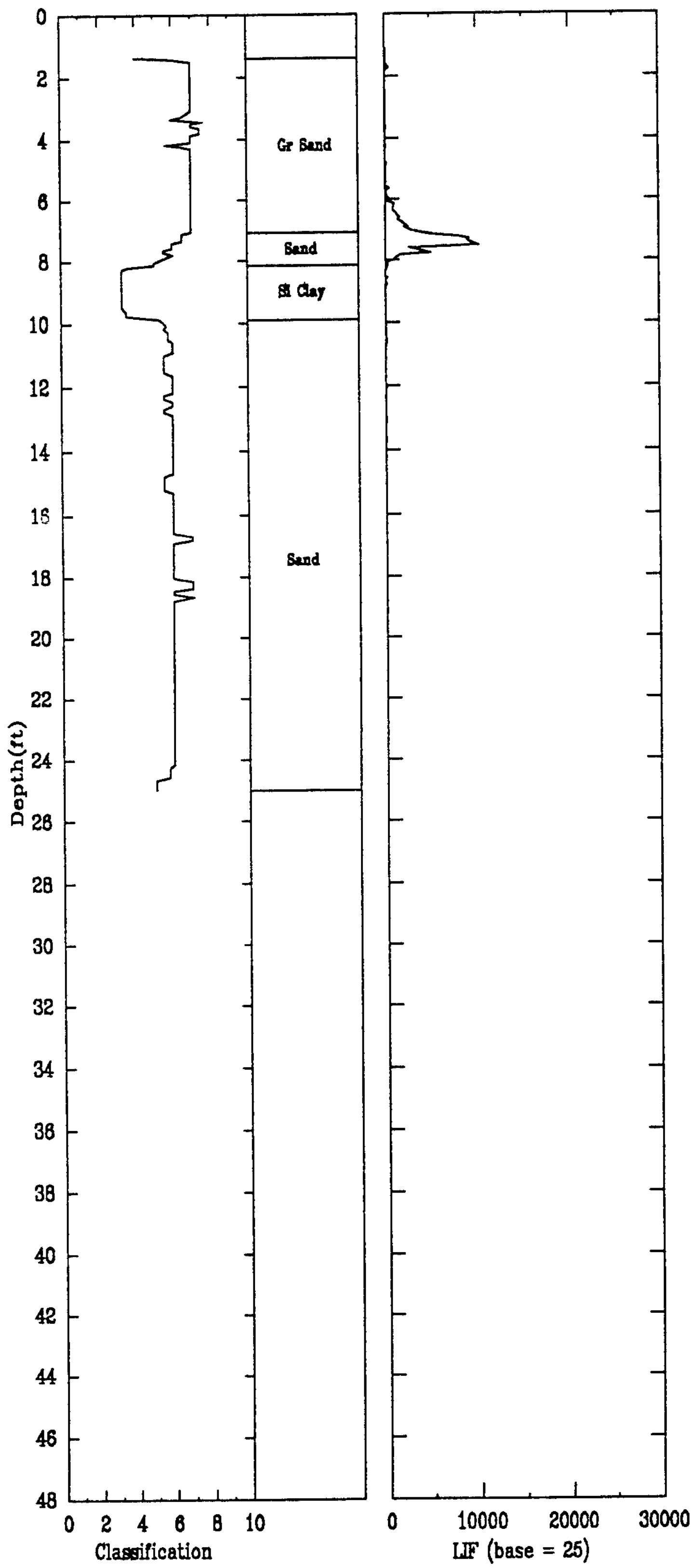
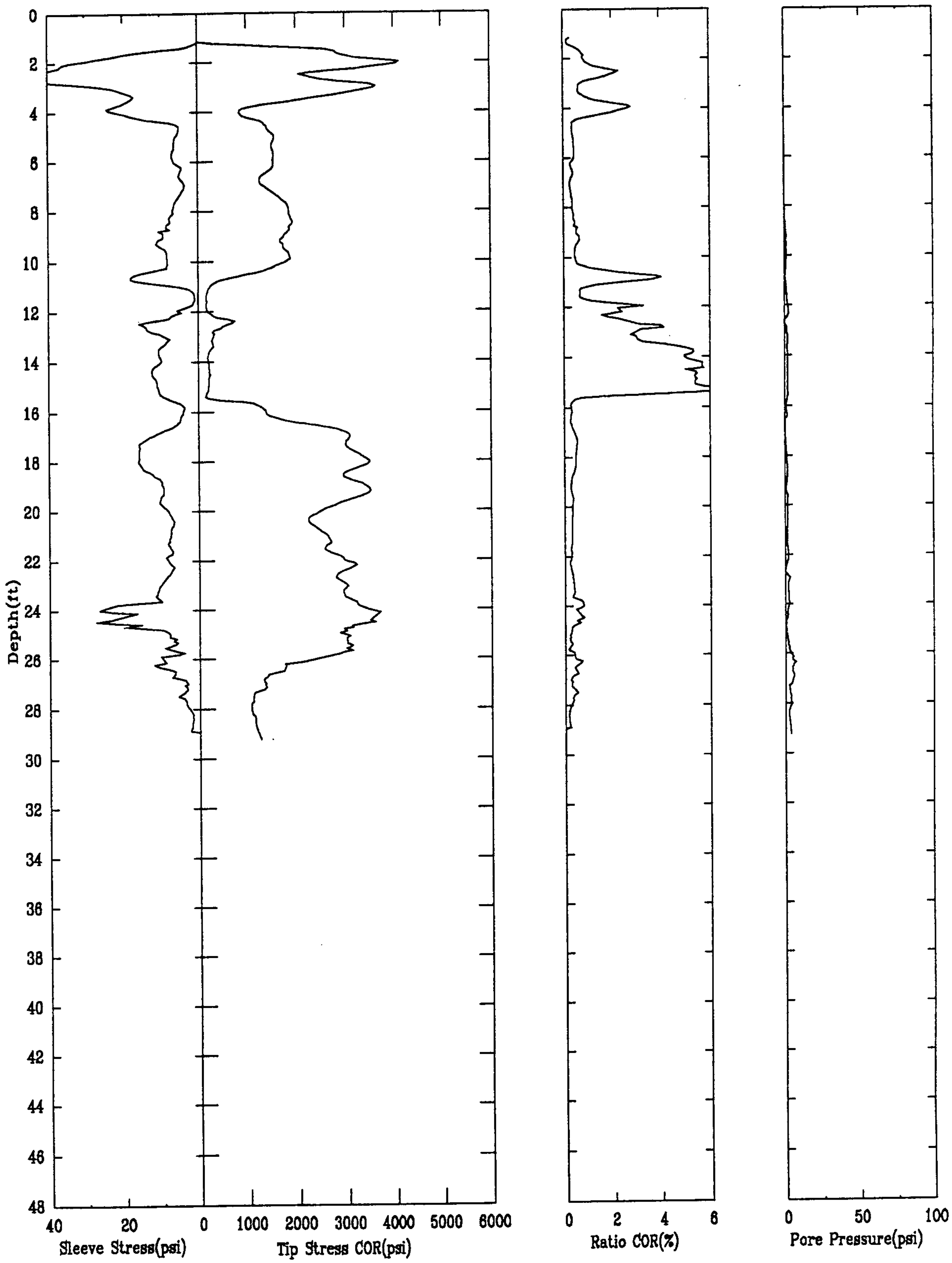


Dover Air Force Base




Depth(ft)
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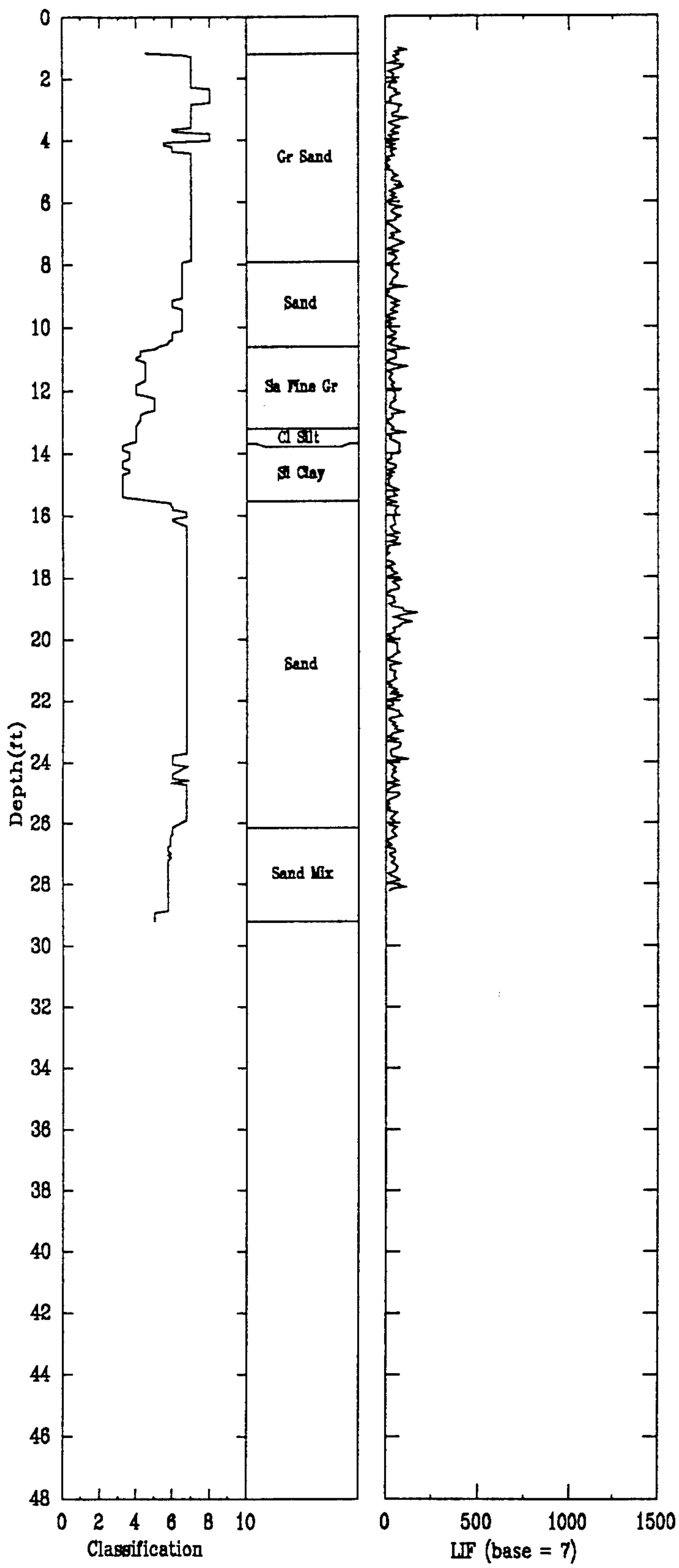
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
40
20
0
Sleeve Stress(psi)
0
1000
2000
3000
4000
5000
6000
Tip Stress COR(psi)
0
2
4
6
Ratio COR(%)
0
50
100
Pore Pressure(psi)


Depth(ft)
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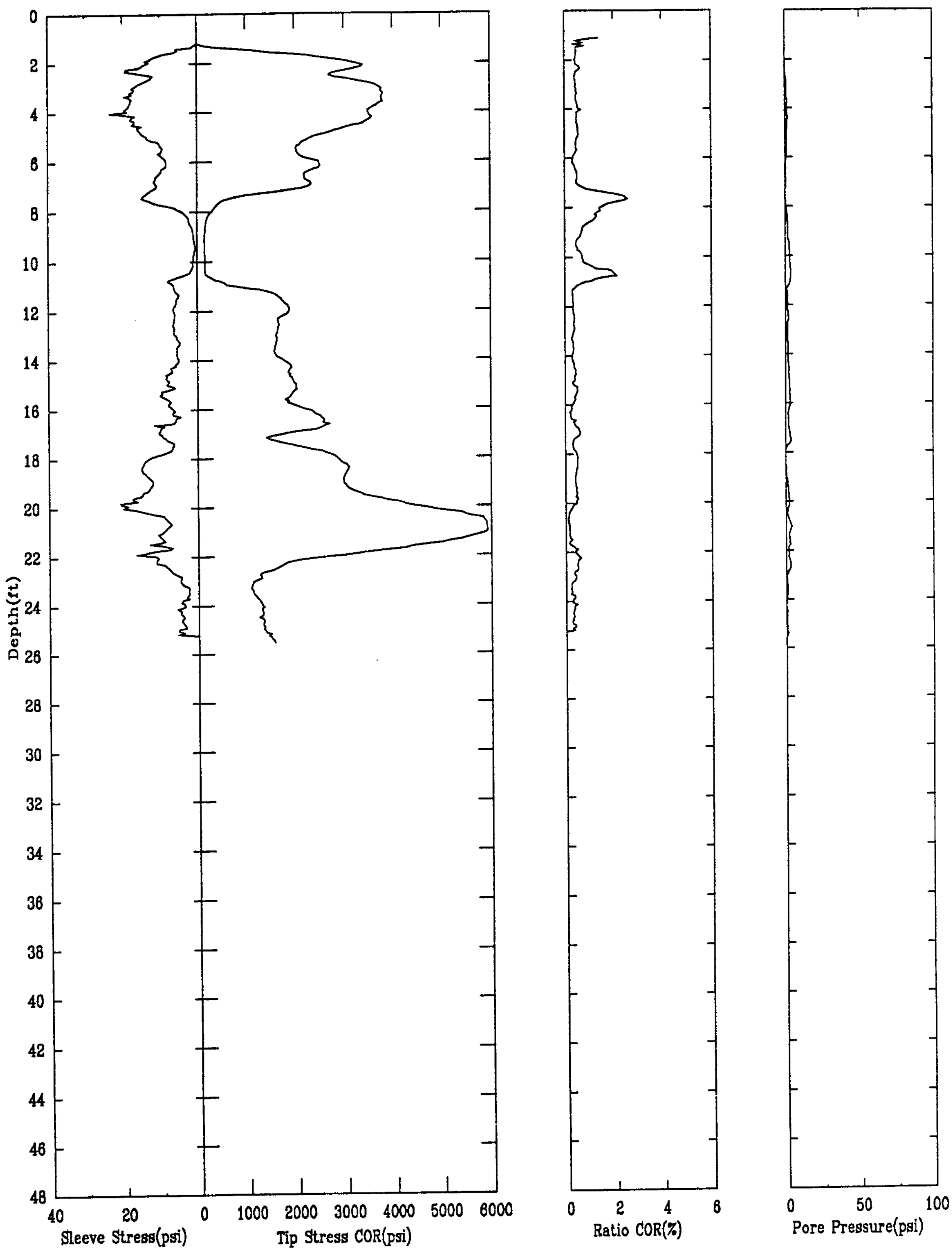
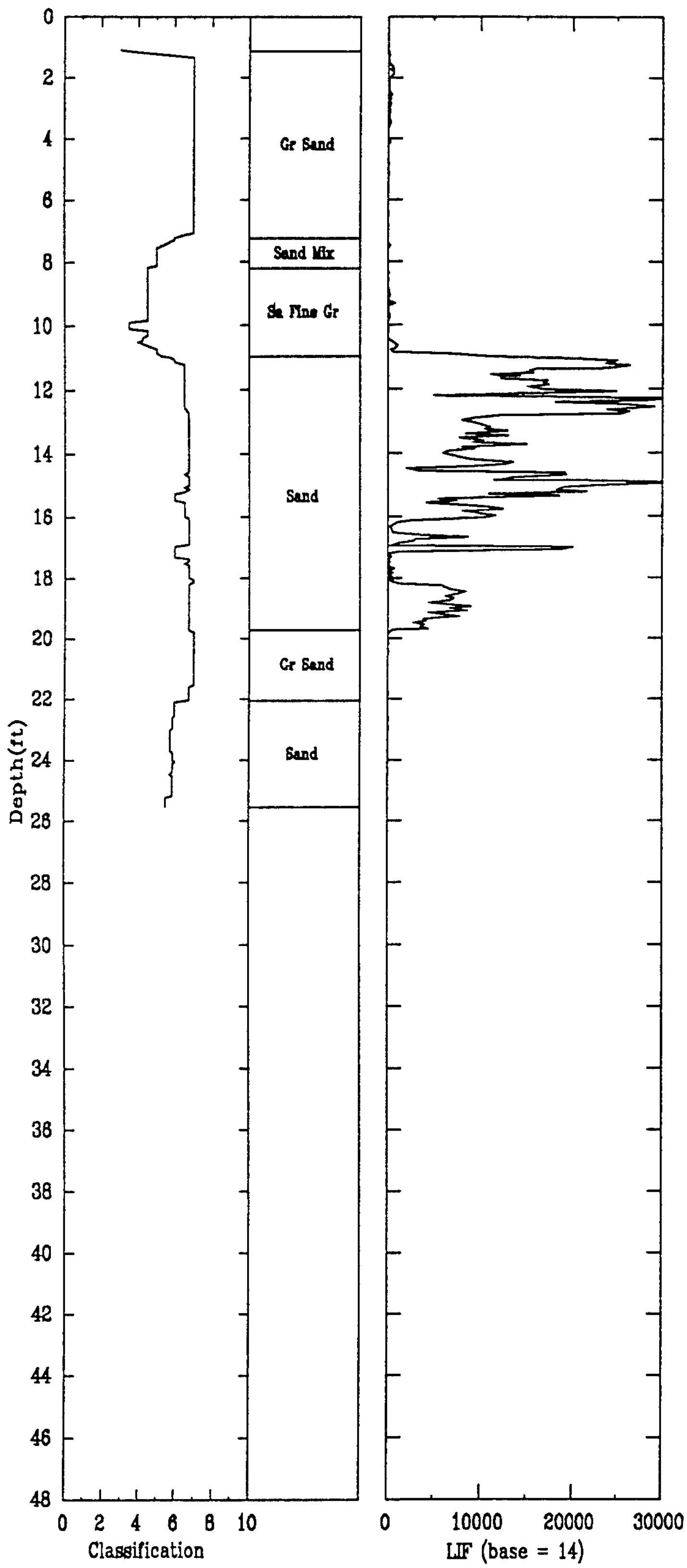
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
Gr Sand
Sand
Sa Fine Gr
Cl Silt
Si Clay
Sand
Sand Mix
0 2 4 6 8 10
Classification
0 500 1000 1500
LIF (base = 7)

Dover Air Force Base

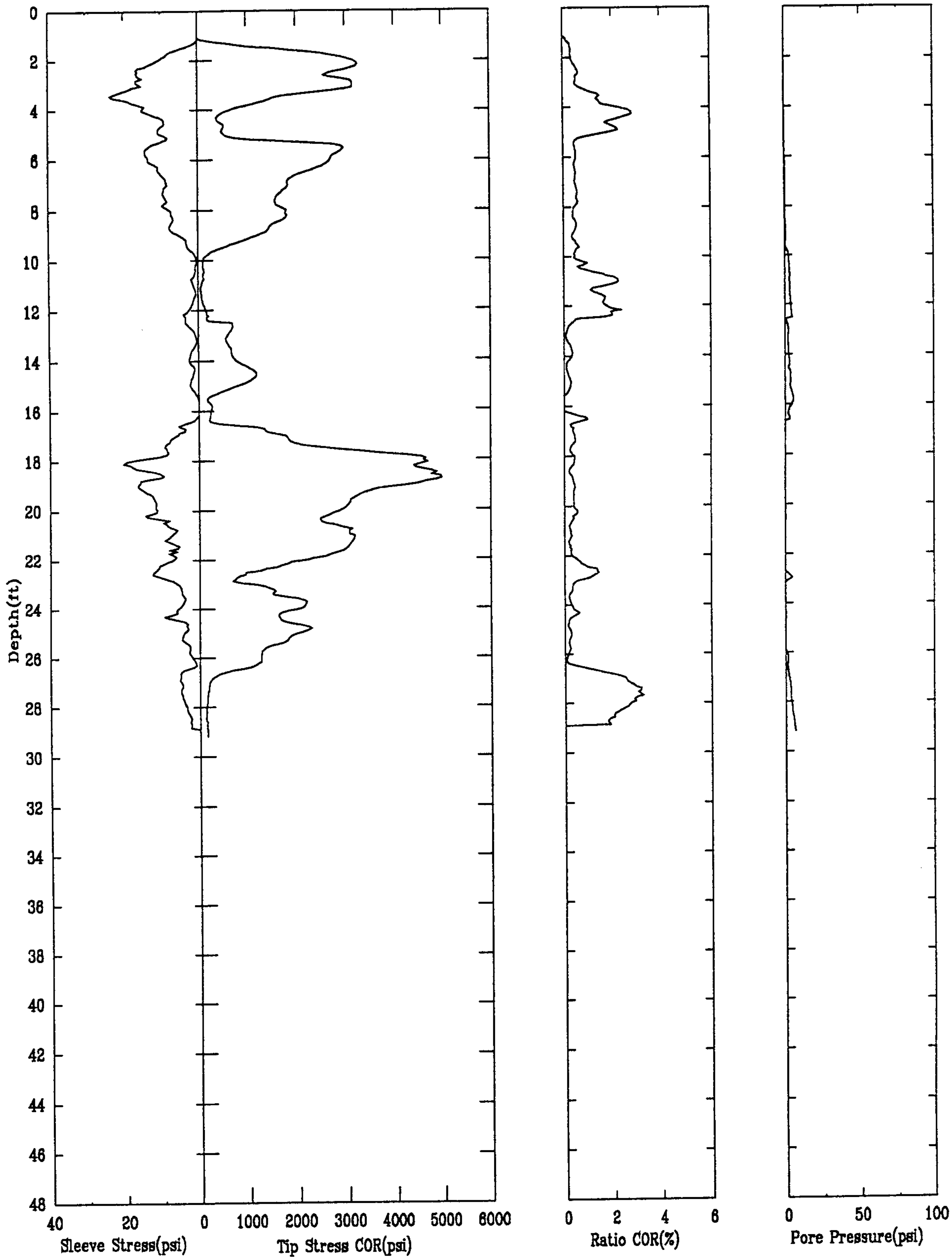


Dover Air Force Base

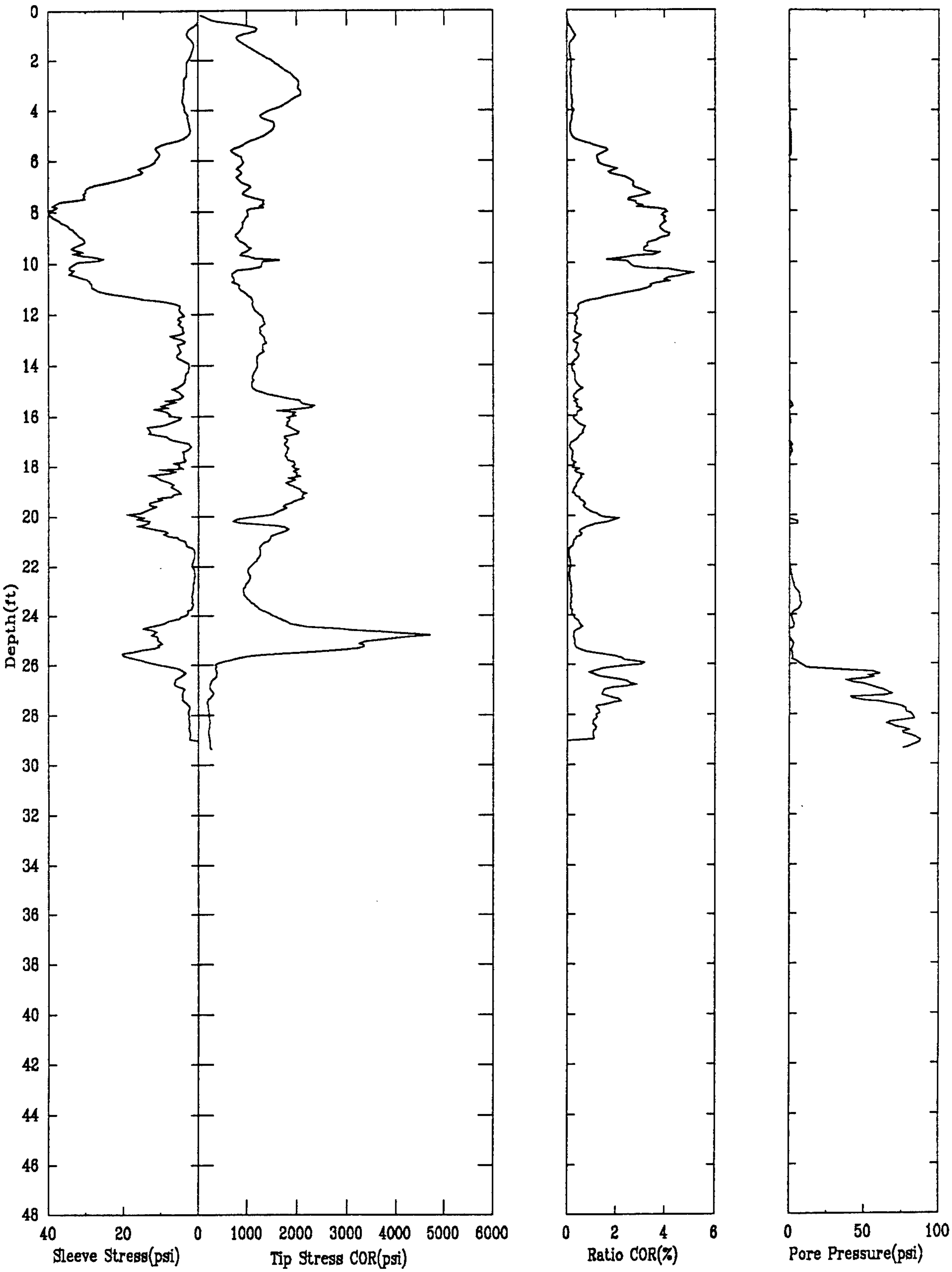


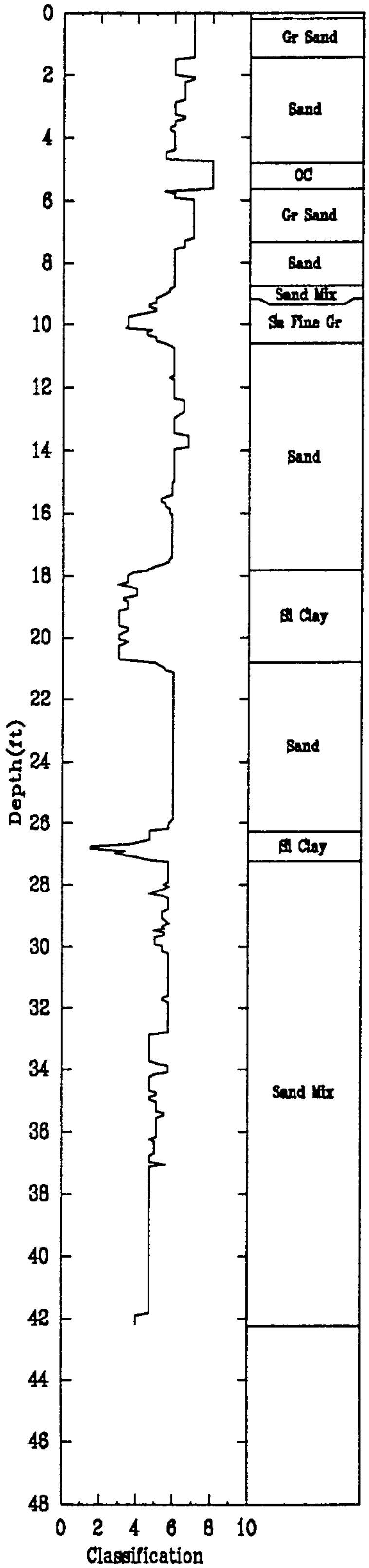
XYZ-CPT-19-LIF APPLIED RESEARCH ASSOCIATES, INC. 04/14/94

Dover Air Force Base

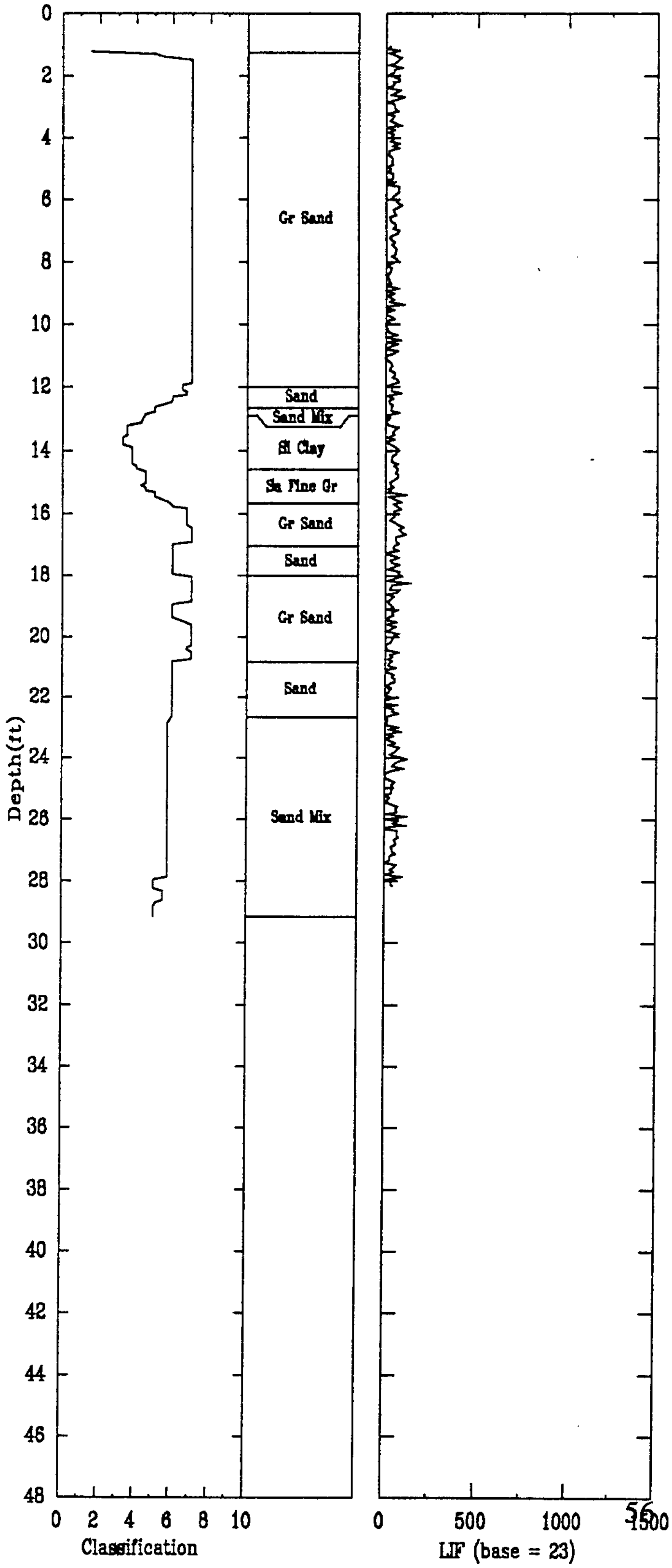


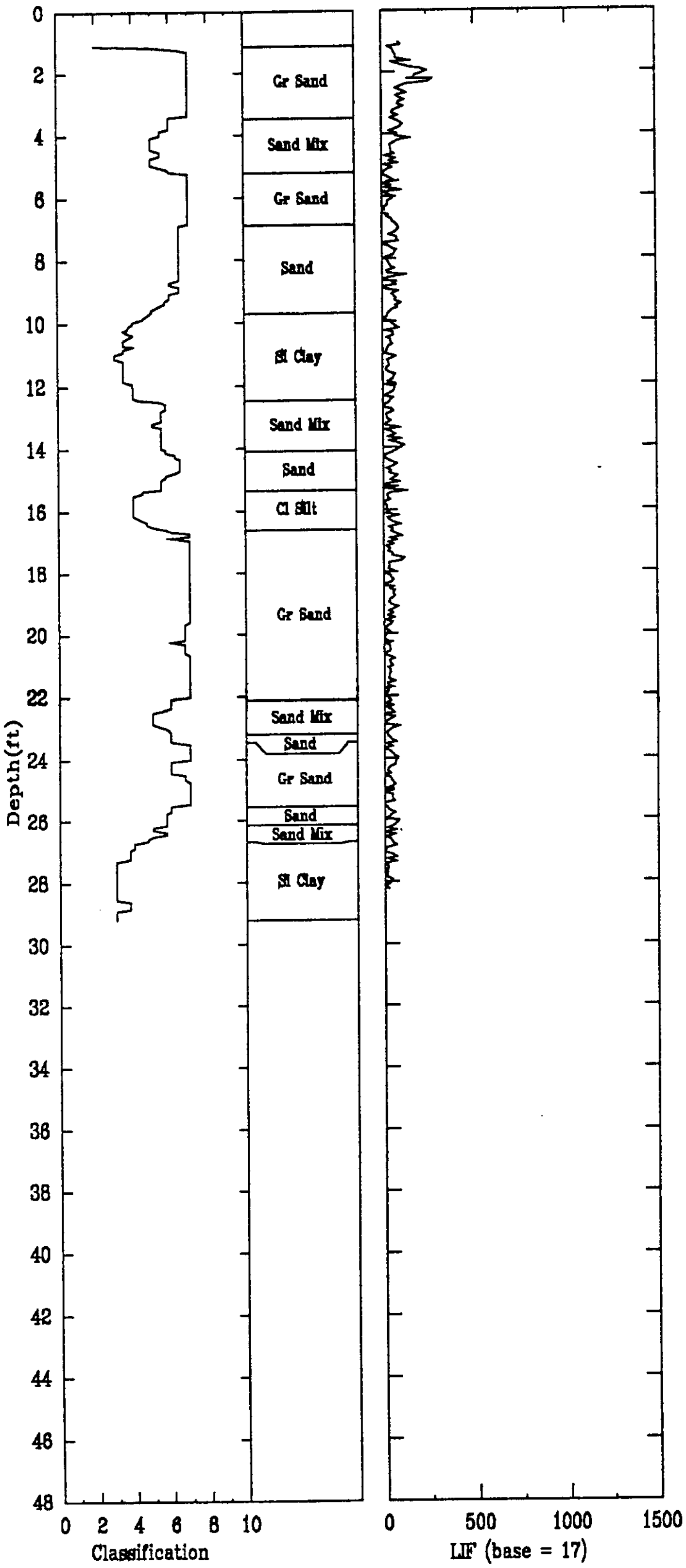
Dover Air Force Base




Gr Sand
Sand
OC
Gr Sand
Sand
Sand Mix
Sa Fine Gr
Sand
Sl Clay
Sand
Sl Clay
Sand Mix
Depth(ft)
Classification
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48

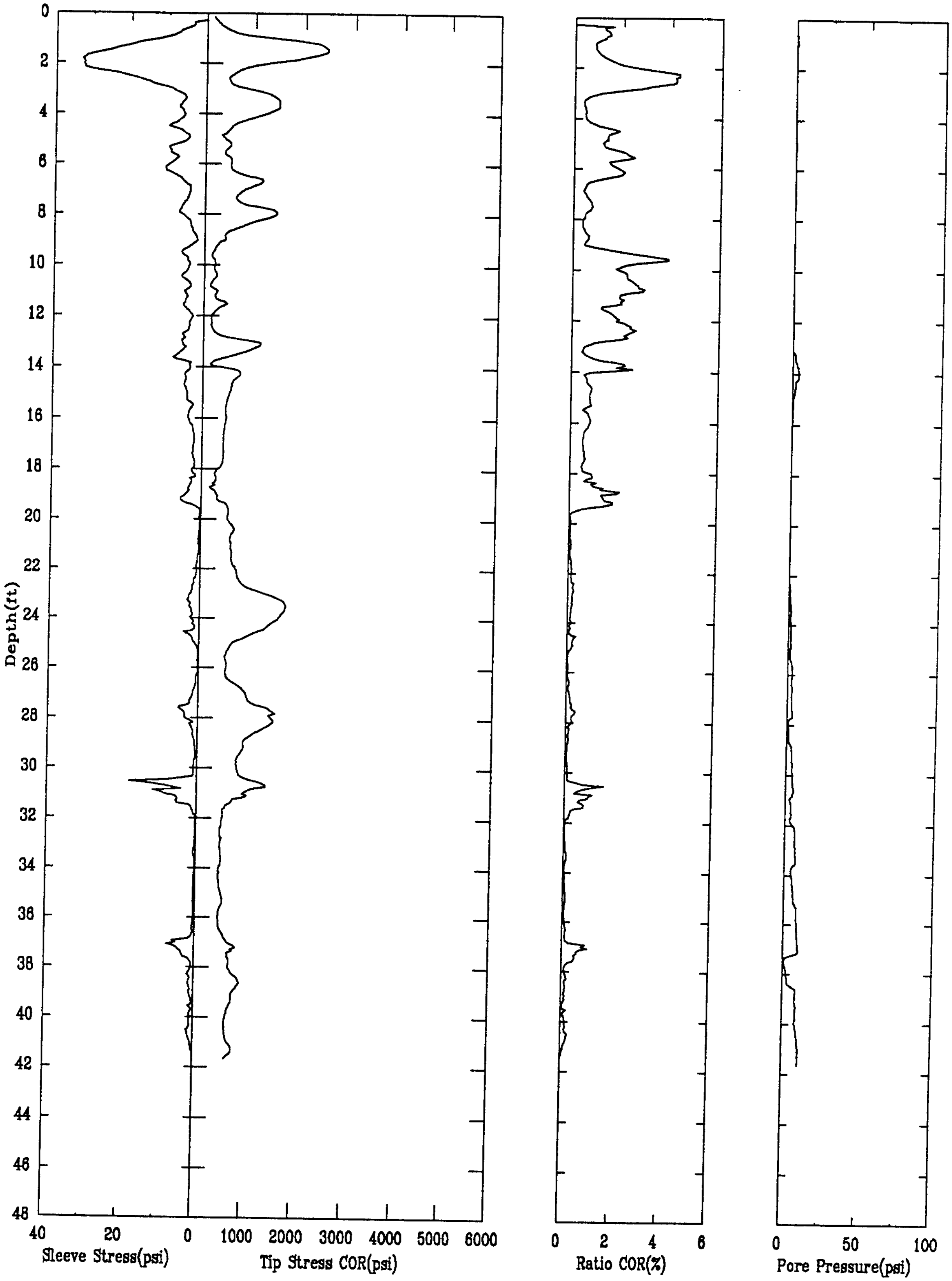
Dover Air Force Base



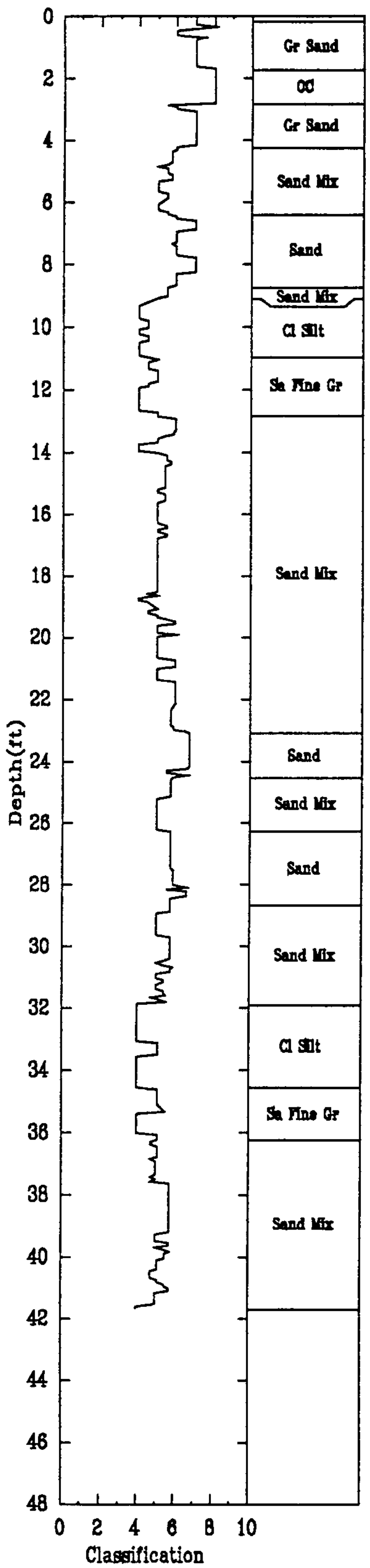

Depth(ft)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
Gr Sand
Sand Mix
Gr Sand
Sand
Sl Clay
Sand Mix
Sand
Cl Silt
Gr Sand
Sand Mix
Sand
Gr Sand
Sand
Sand Mix
Sl Clay
0 2 4 6 8 10
Classification
0 500 1000 1500
LIF (base = 17)

D7-CPT-01 APPLIED RESEARCH ASSOCIATES, INC. 04/19/94

Dover Air Force Base

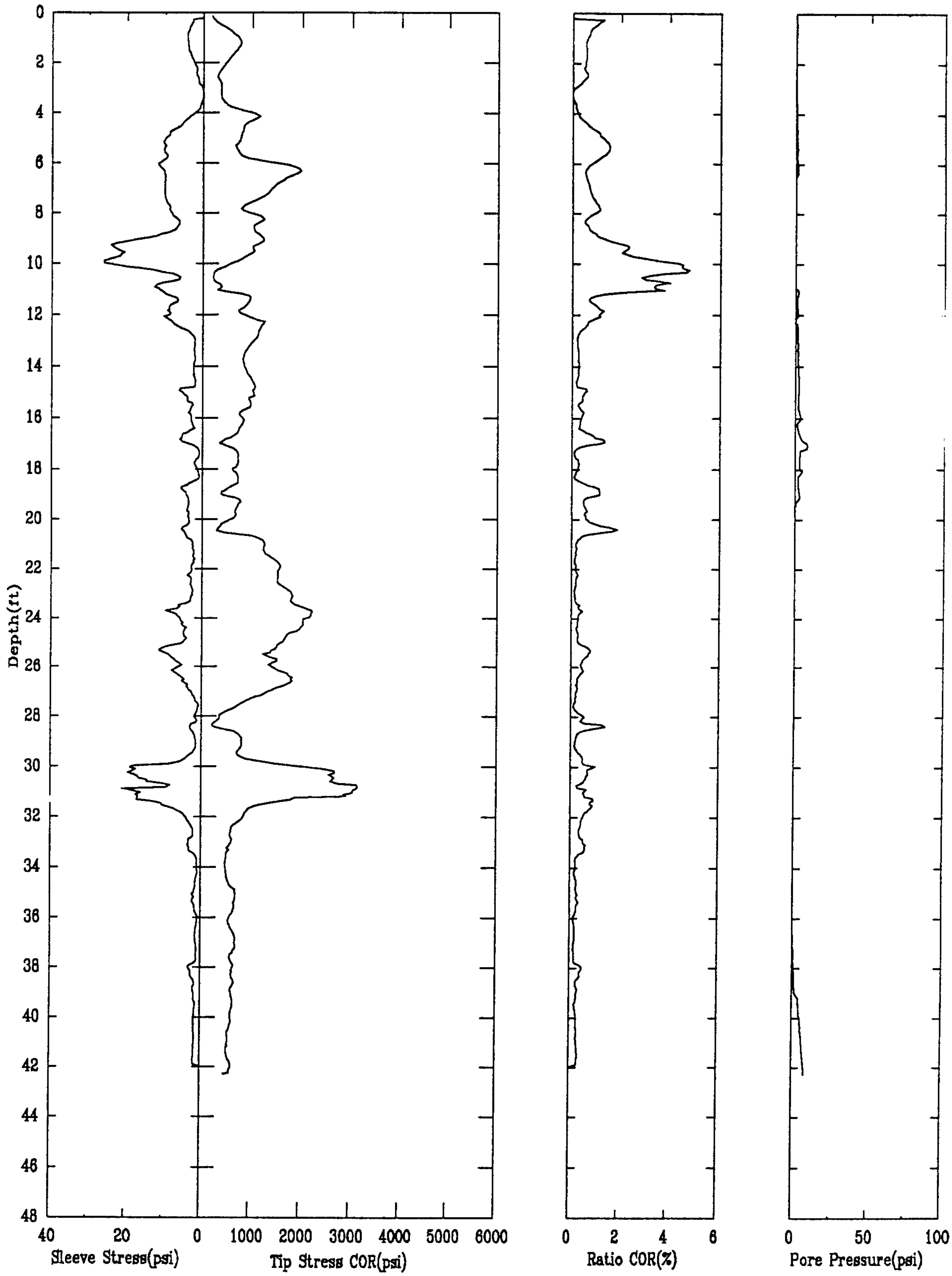


Dover Air Force Base

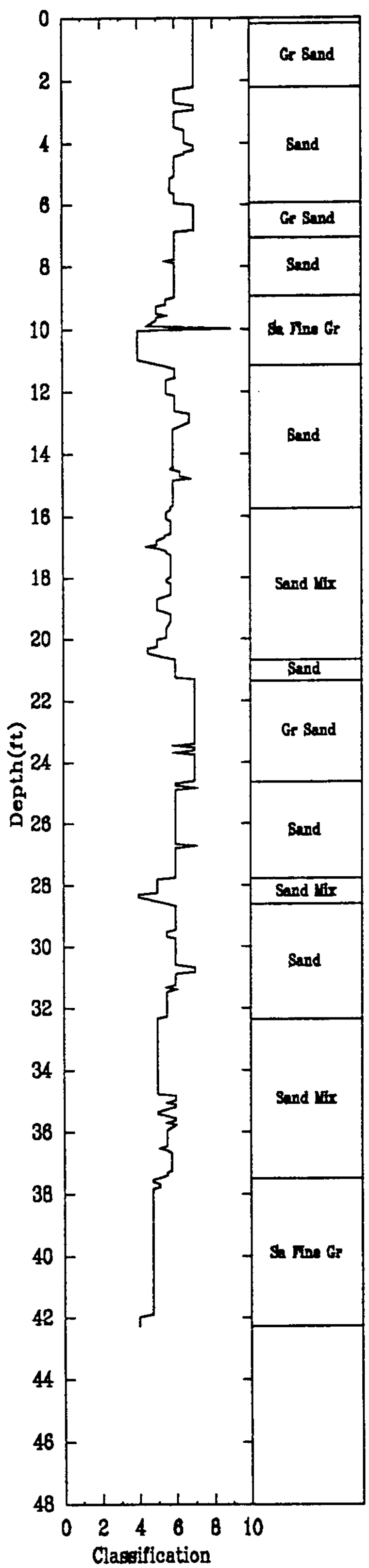


D7-CPT-02 APPLIED RESEARCH ASSOCIATES, INC. 04/19/94

Dover Air Force Base

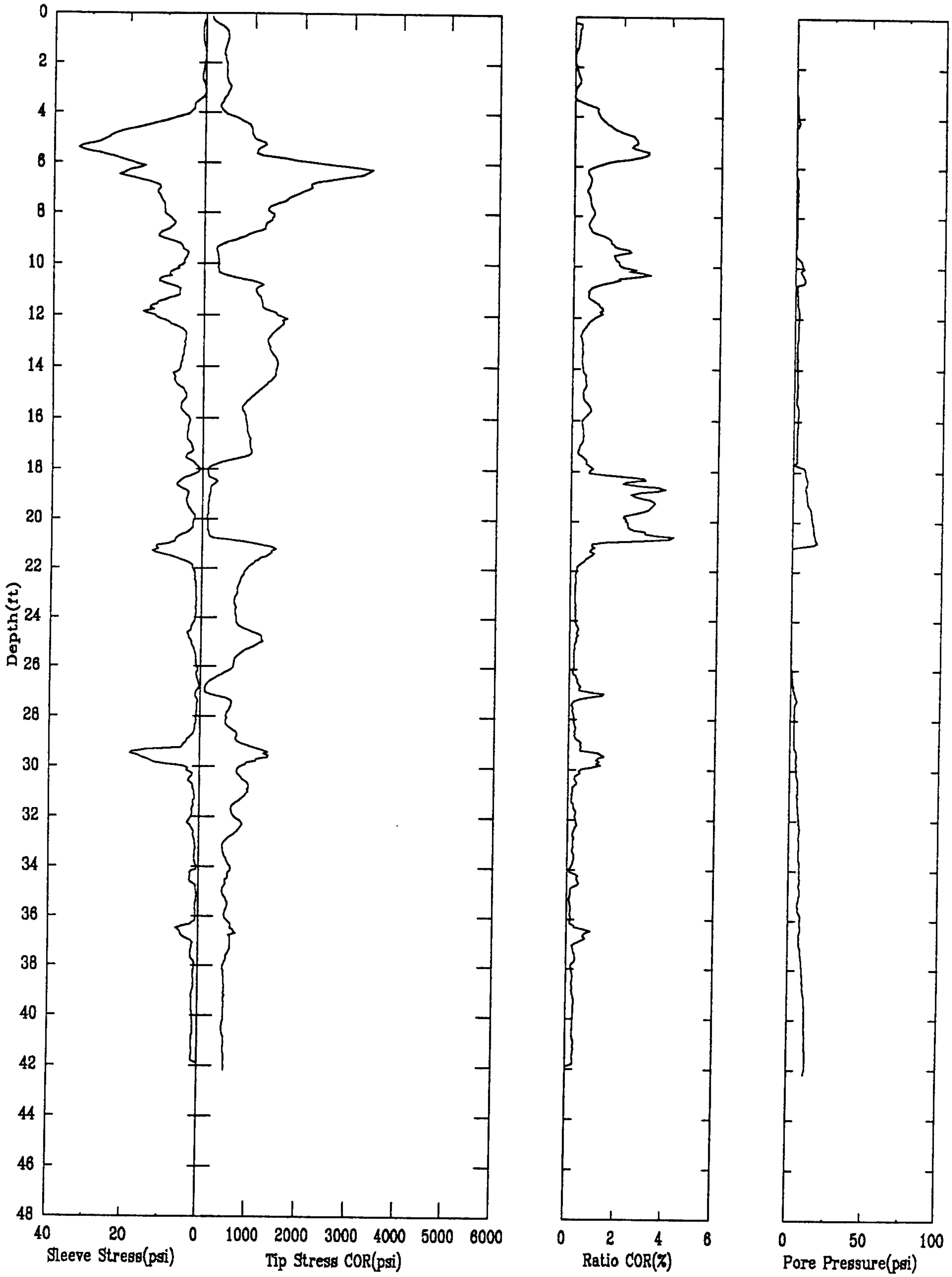


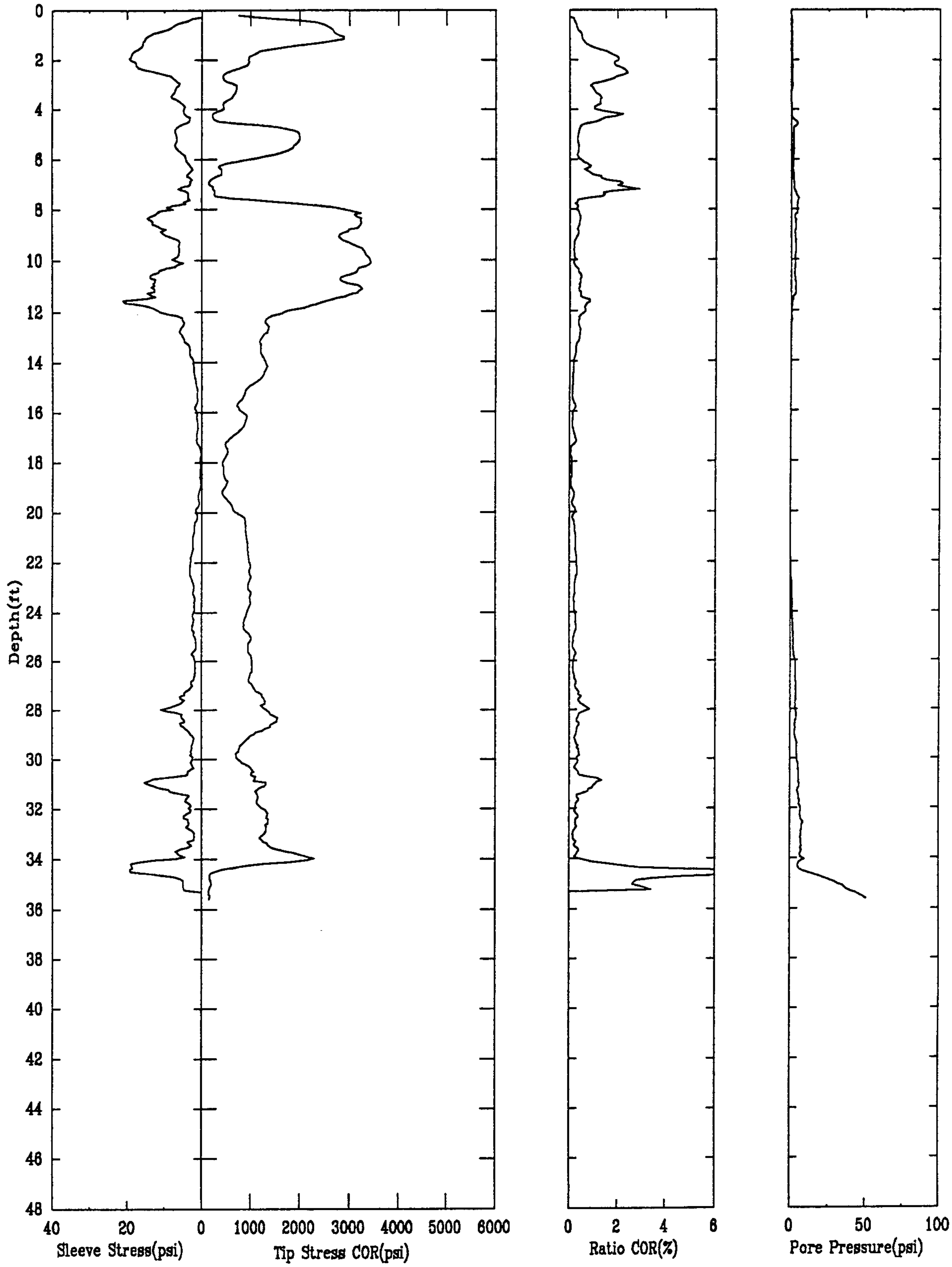
Dover Air Force Base



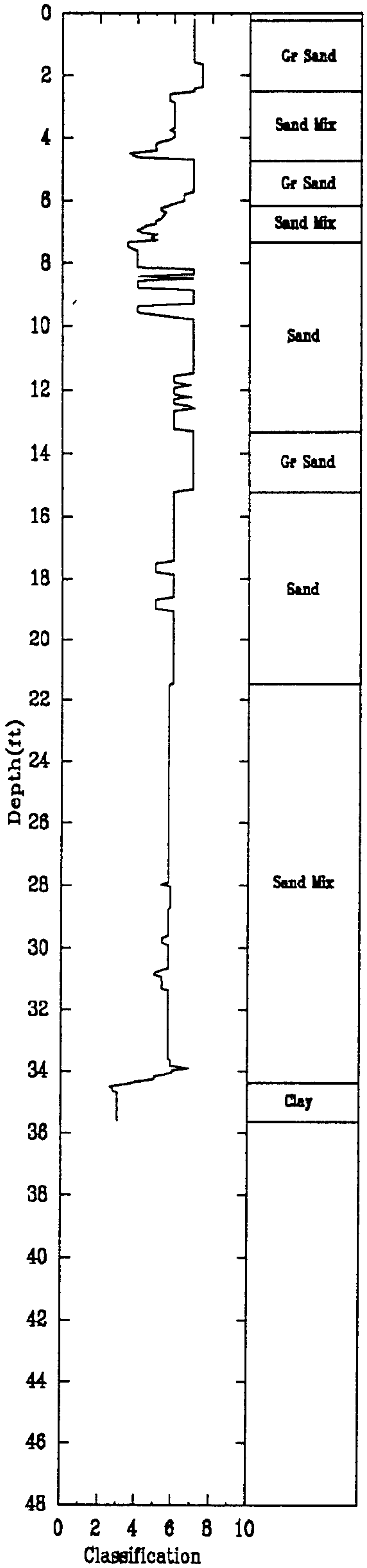
D7-CPT-03 APPLIED RESEARCH ASSOCIATES, INC. 04/19/94

Dover Air Force Base

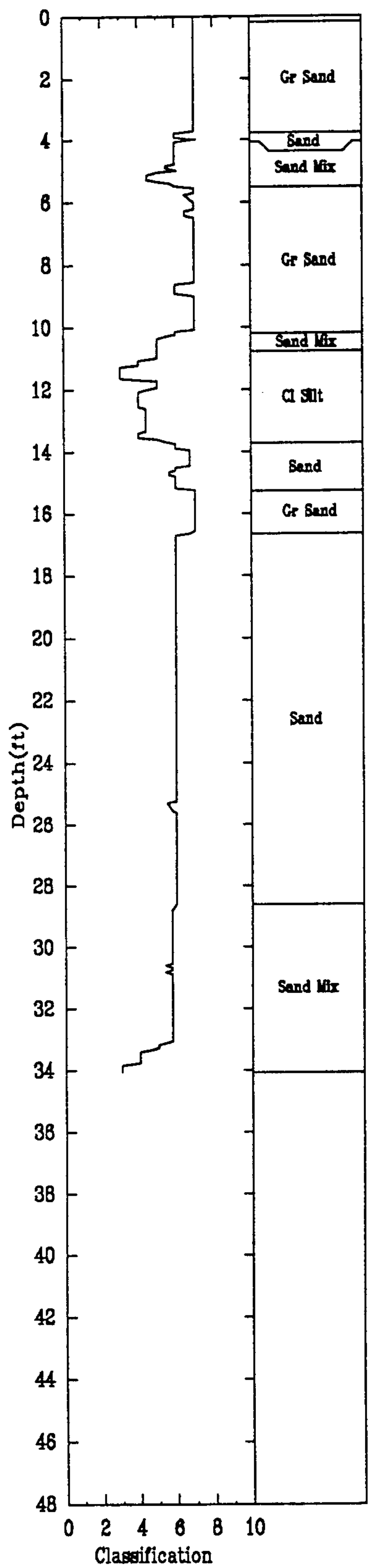



Depth(ft)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
40 20 0
Sleeve Stress(psi)
1000 2000 3000 4000 5000 6000
Tip Stress COR(psi)
0 2 4 6
Ratio COR(%)
0 50 100
Pore Pressure(psi)

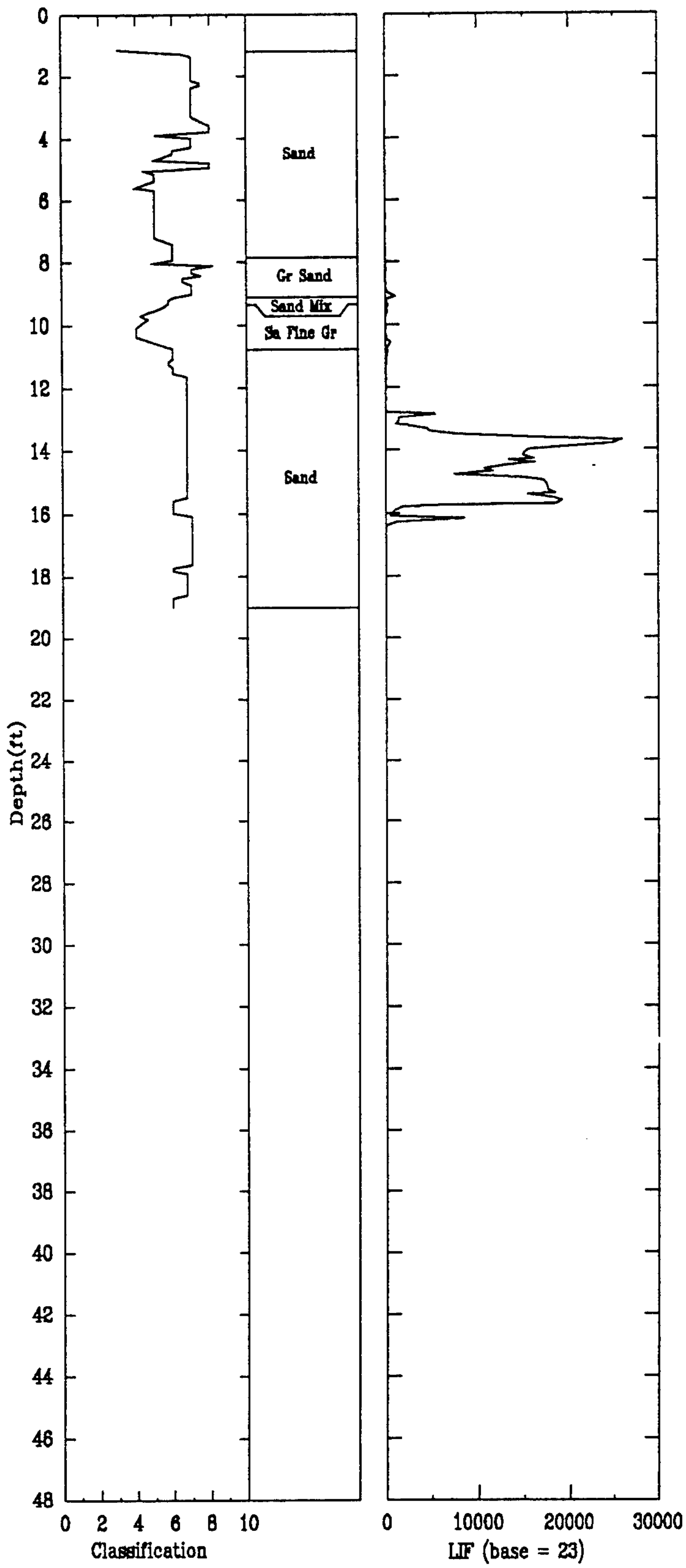
Dover Air Force Base

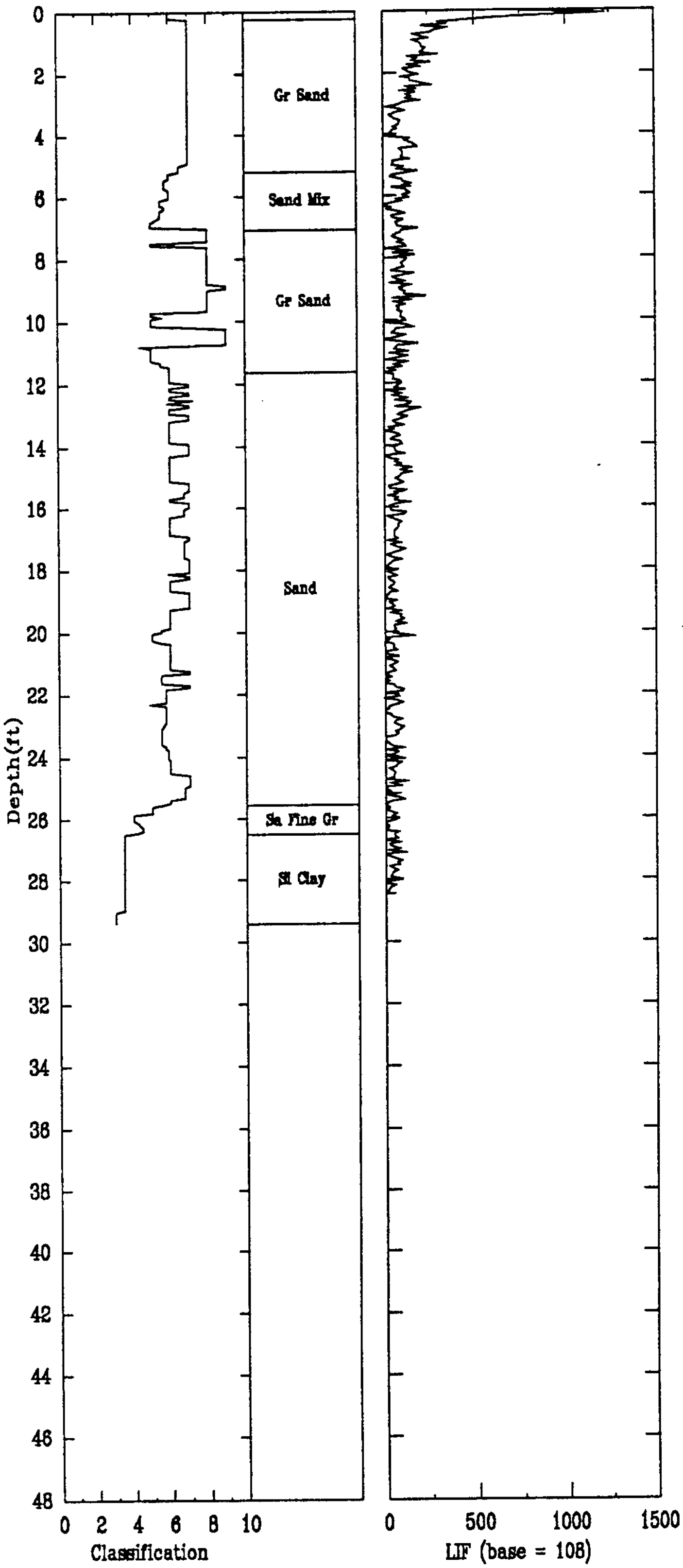


Dover Air Force Base



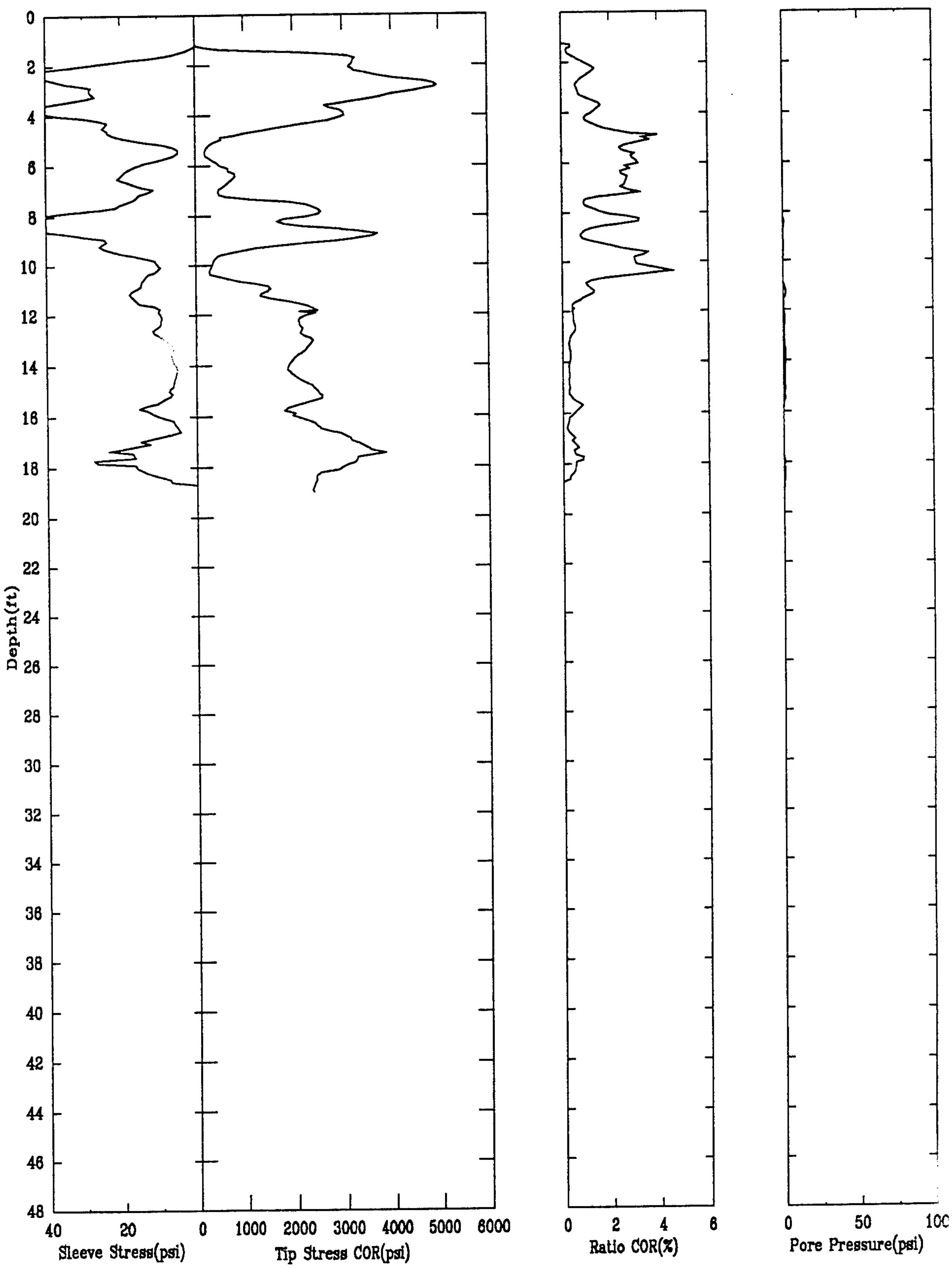
Dover Air Force Base




Depth(ft)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
Gr Sand
Sand Mix
Gr Sand
Sand
Sa Fine Gr
Sl Clay
0 2 4 6 8 10
Classification
0 500 1000 1500
LIF (base = 108)

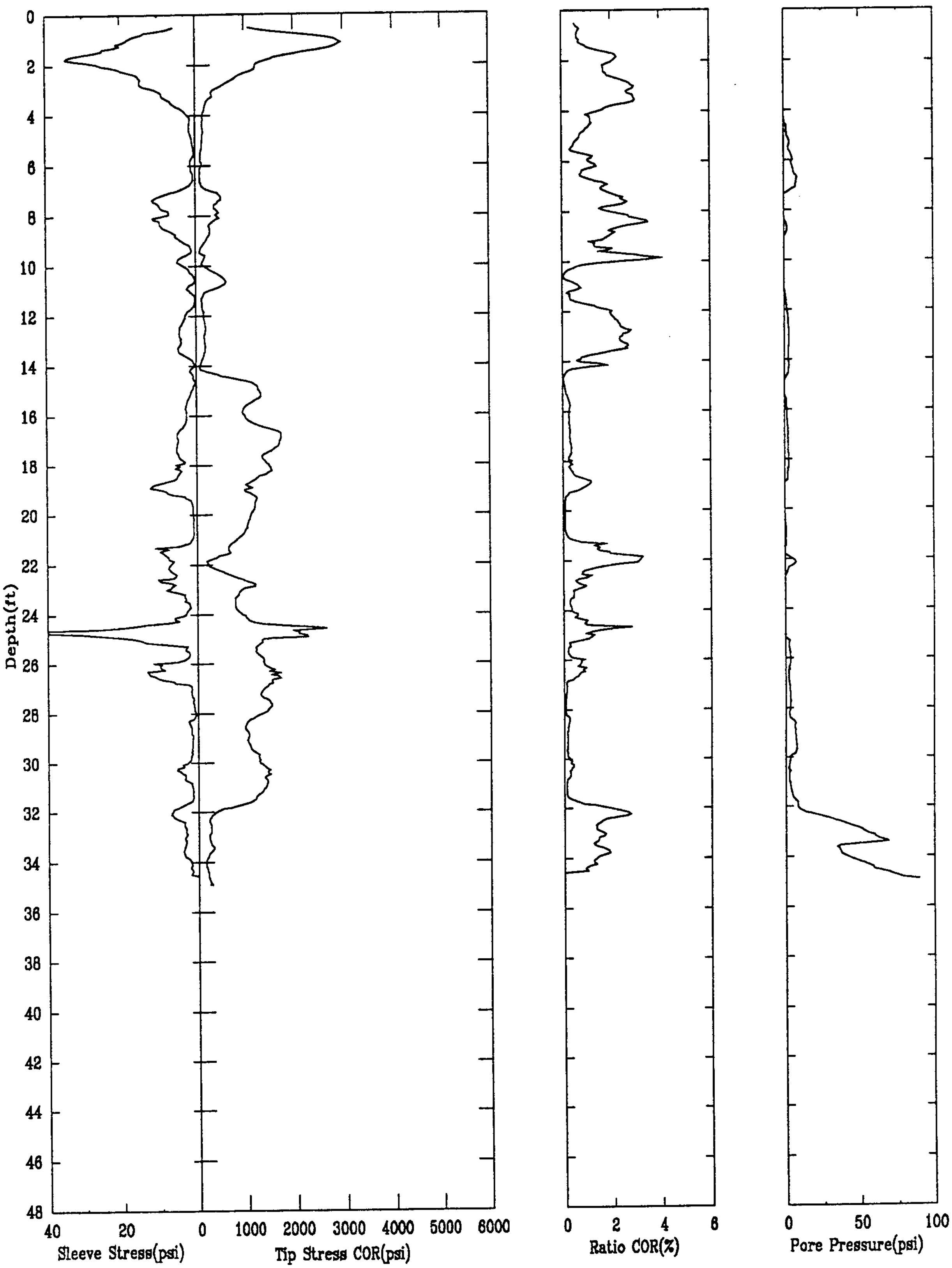
XYZ-CPT-20-LIF APPLIED RESEARCH ASSOCIATES, INC. 04/14/94

Dover Air Force Base



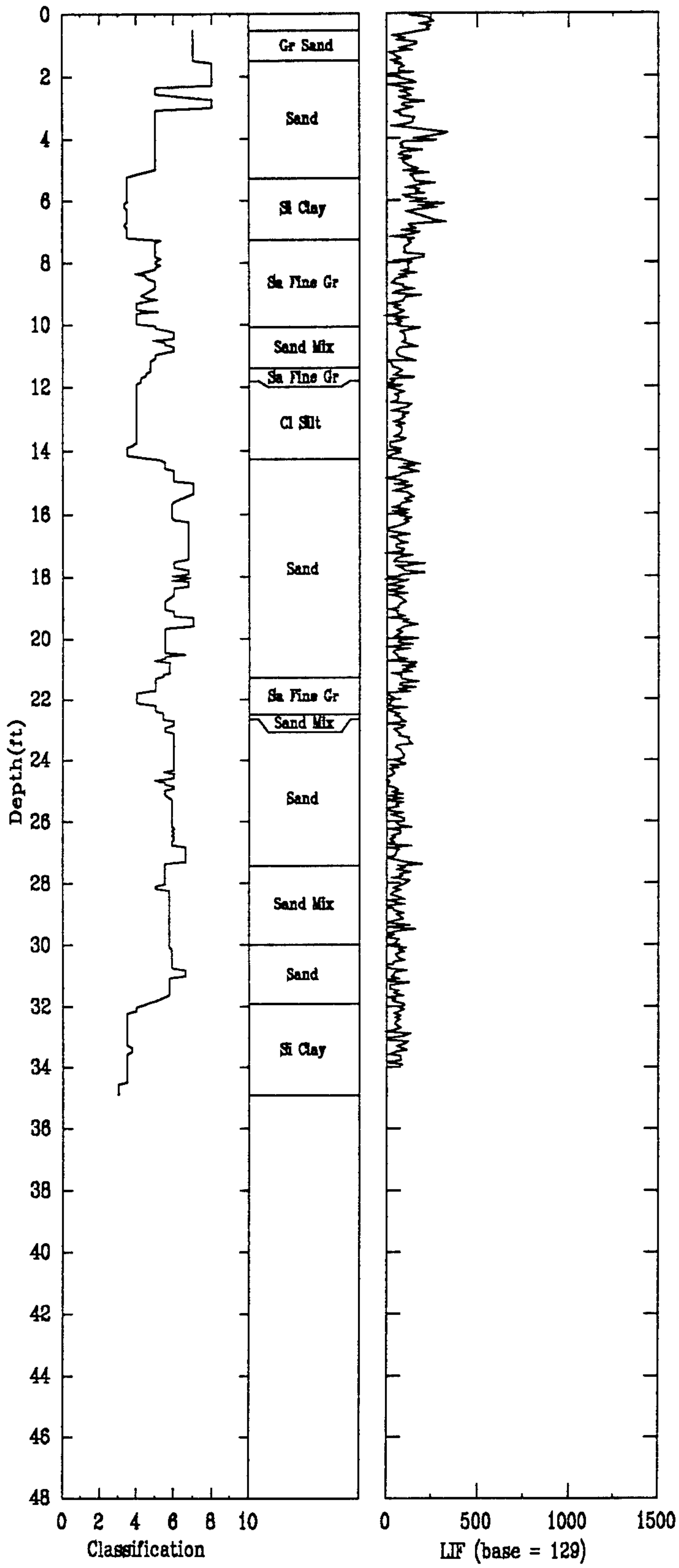
XYZ-CPT-22-LIF APPLIED RESEARCH ASSOCIATES, INC. 04/16/94

Dover Air Force Base

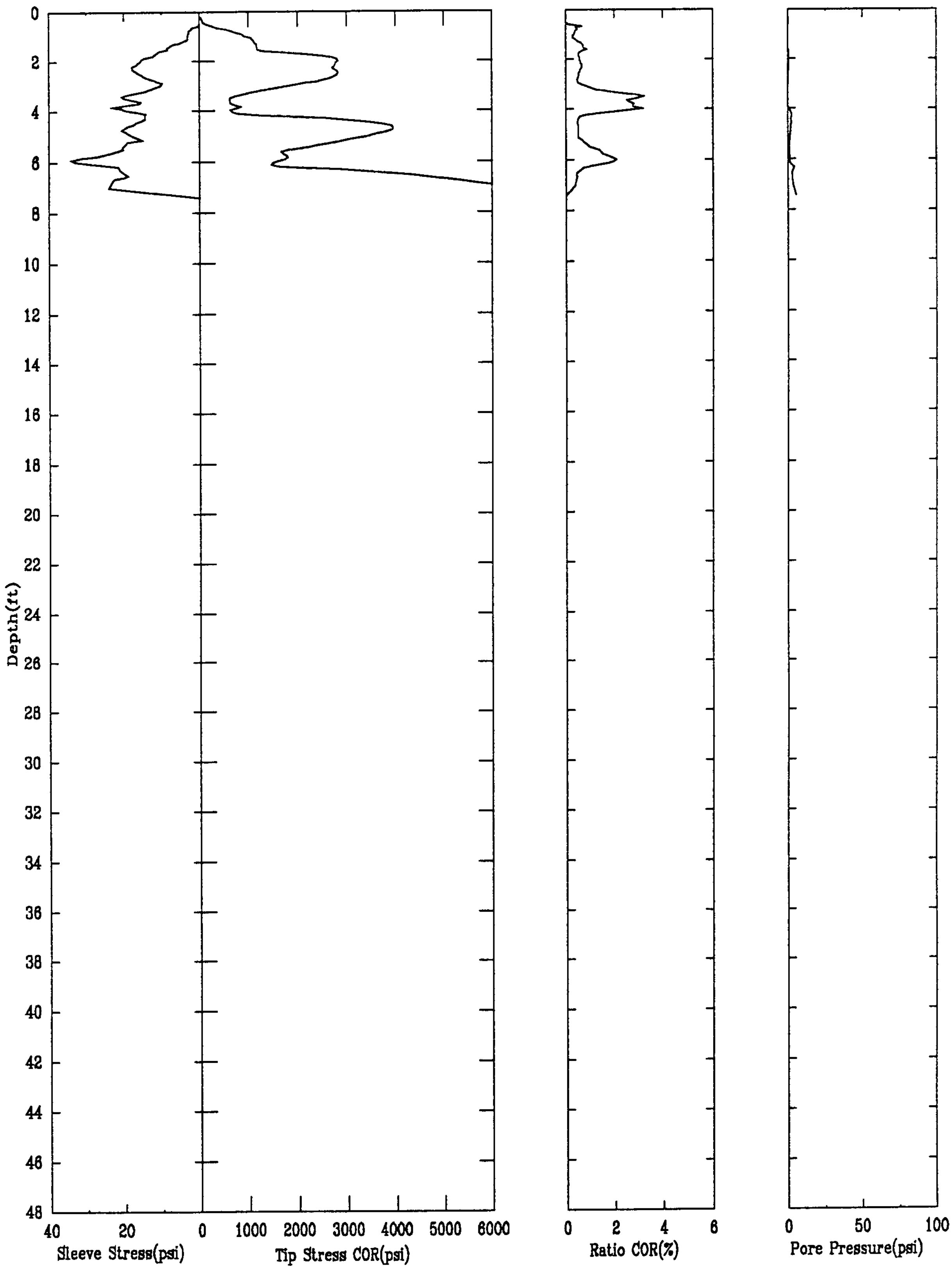


XYZ-CPT-22-LIF APPLIED RESEARCH ASSOCIATES, INC. 04/16/94

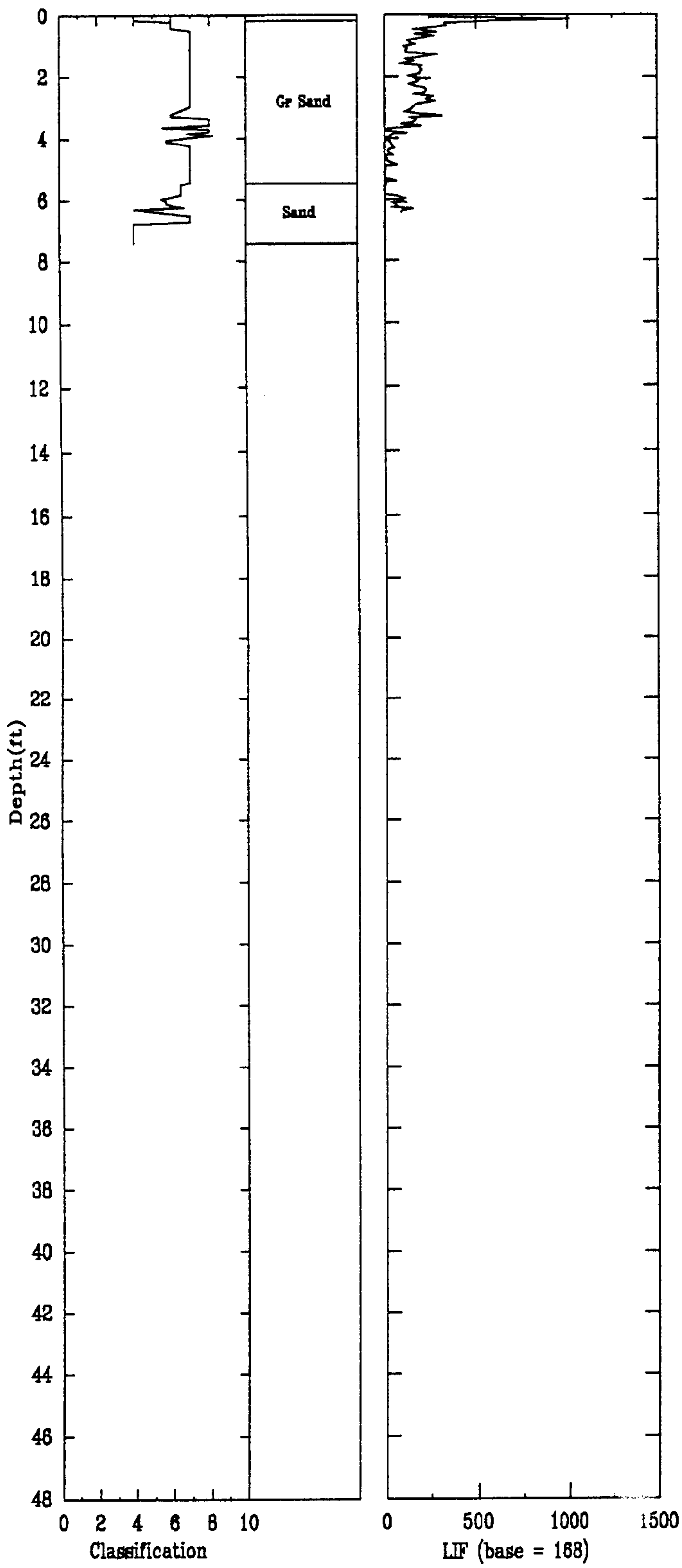
Dover Air Force Base



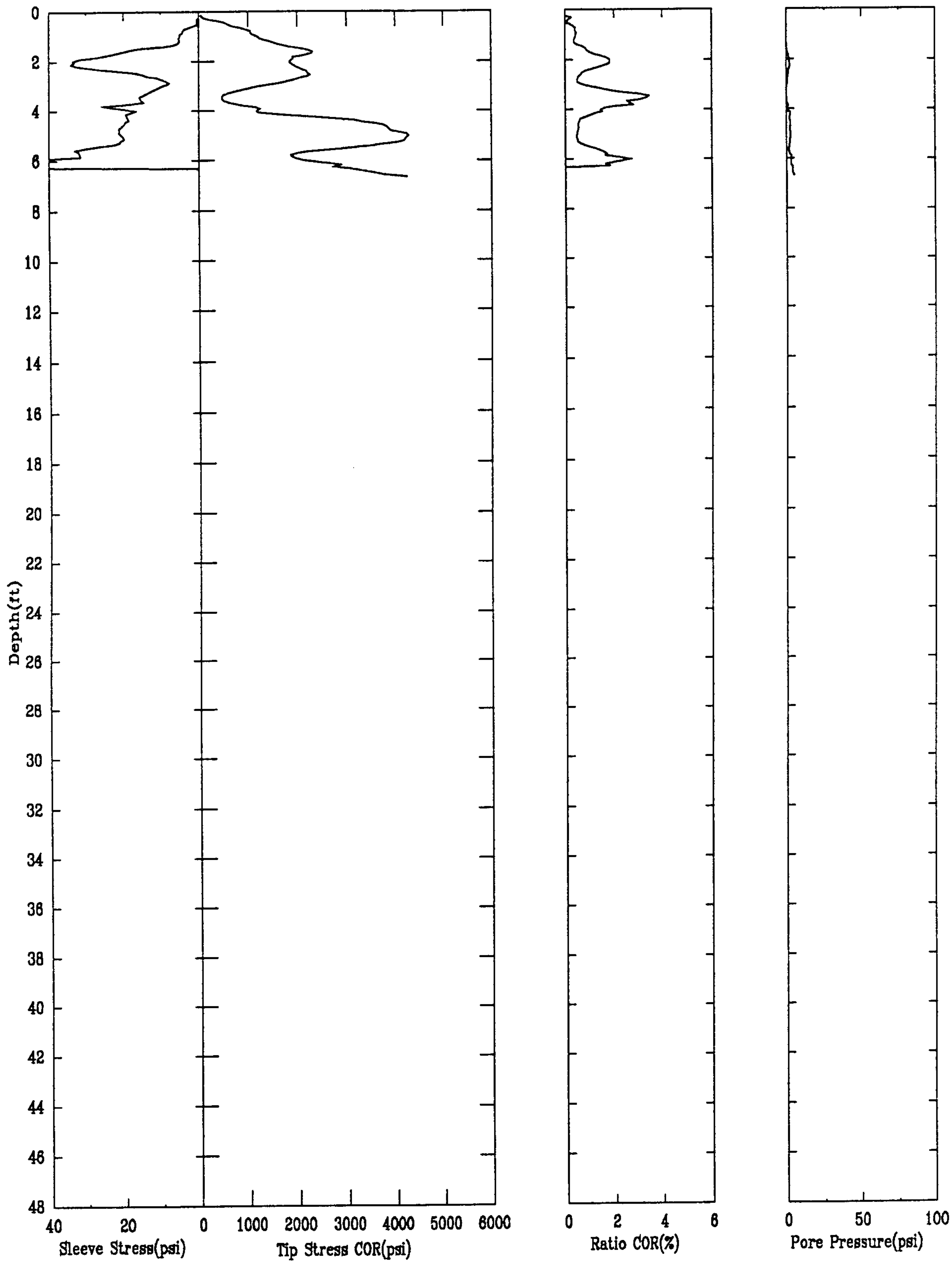
Dover Air Force Base



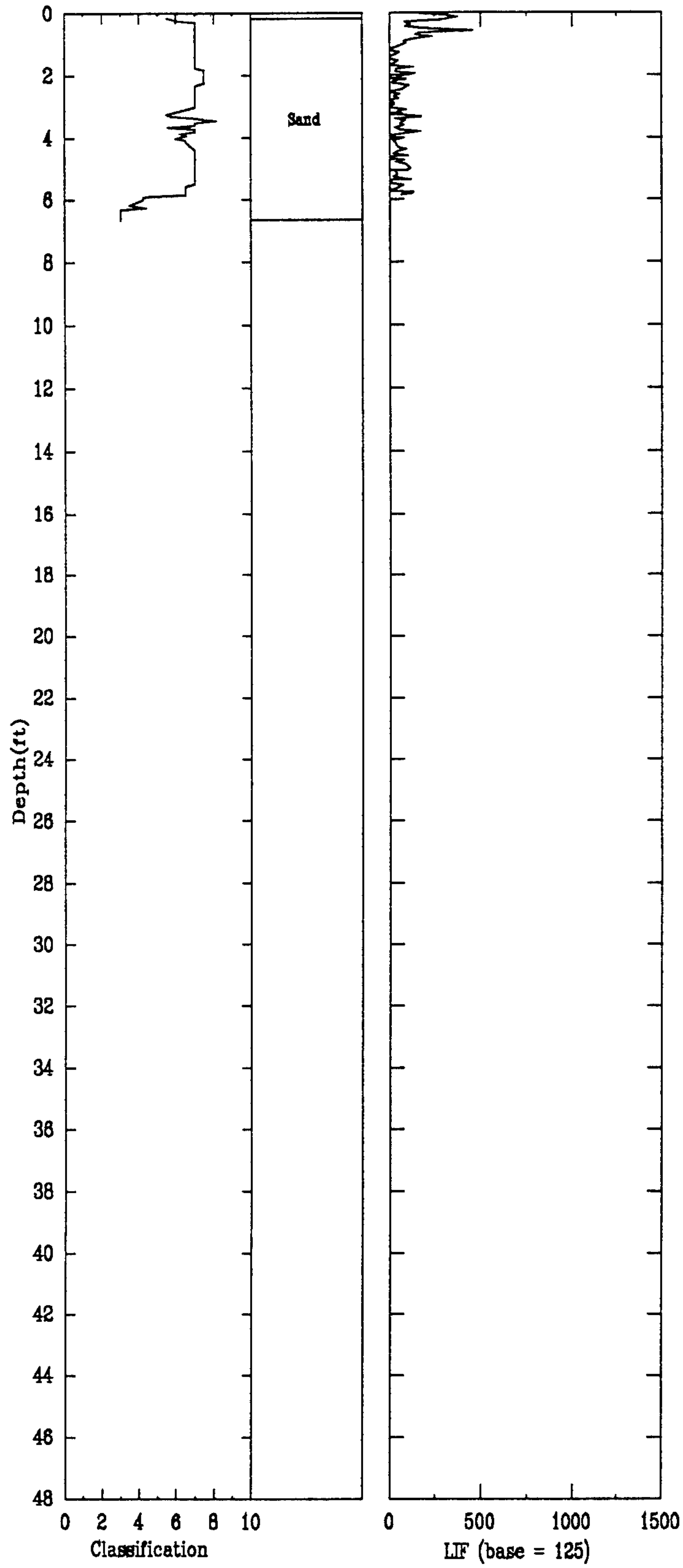
Dover Air Force Base

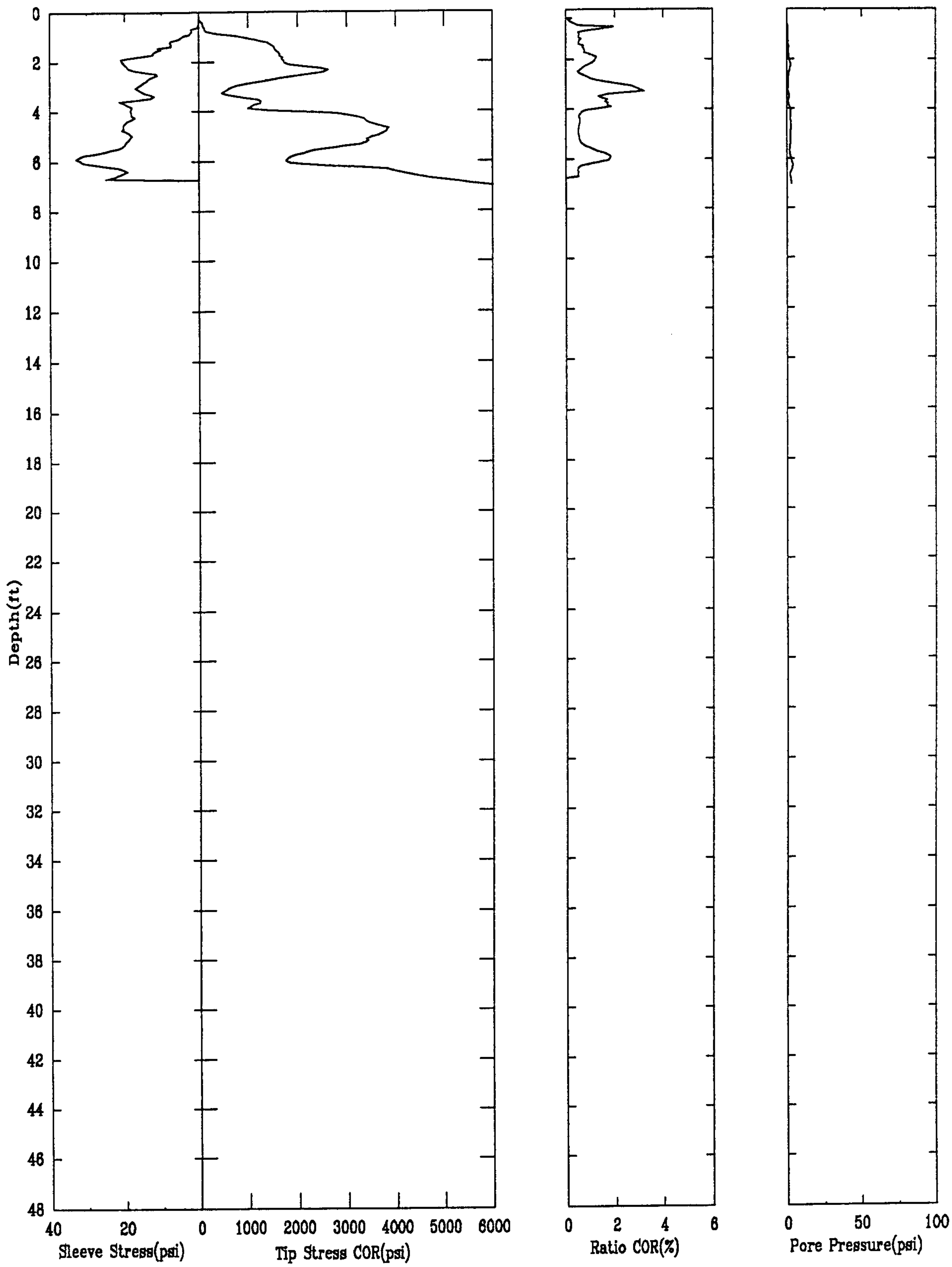


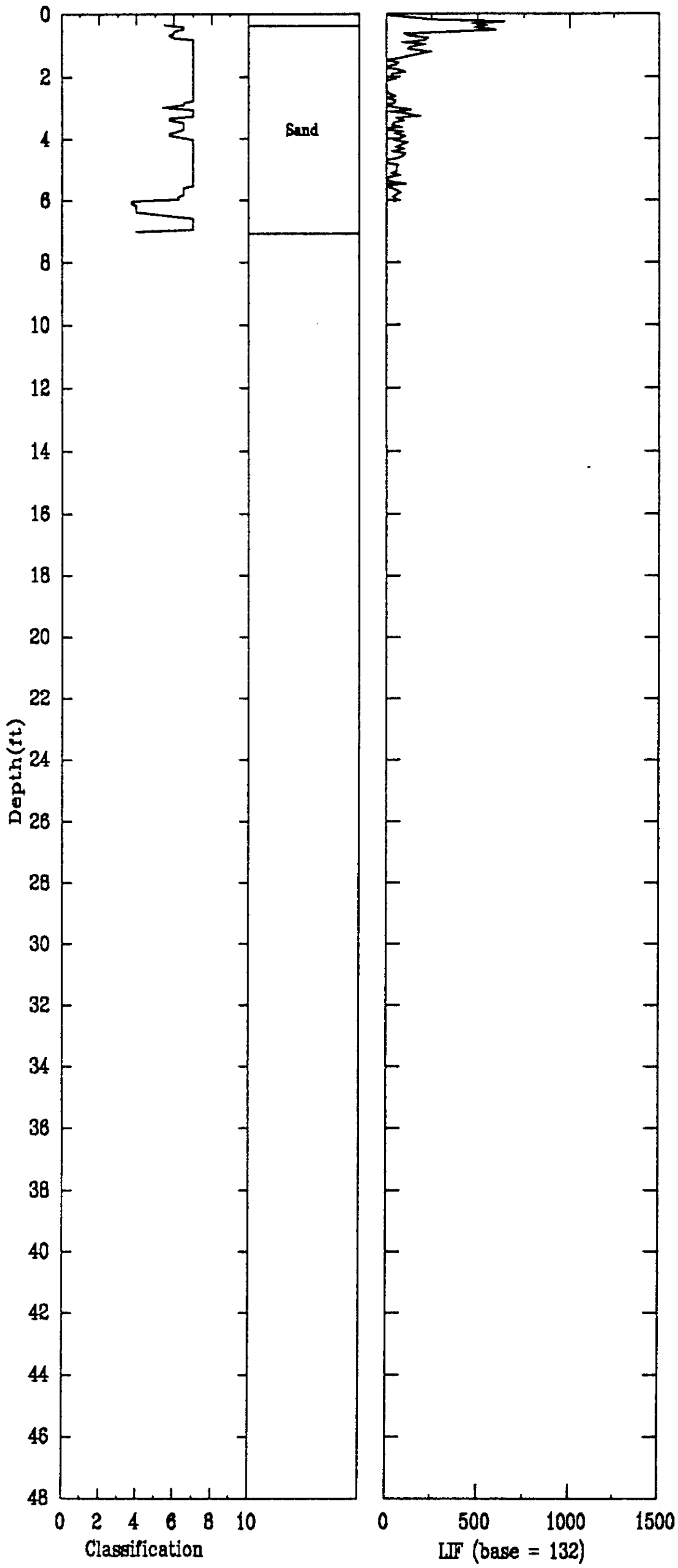
Dover Air Force Base



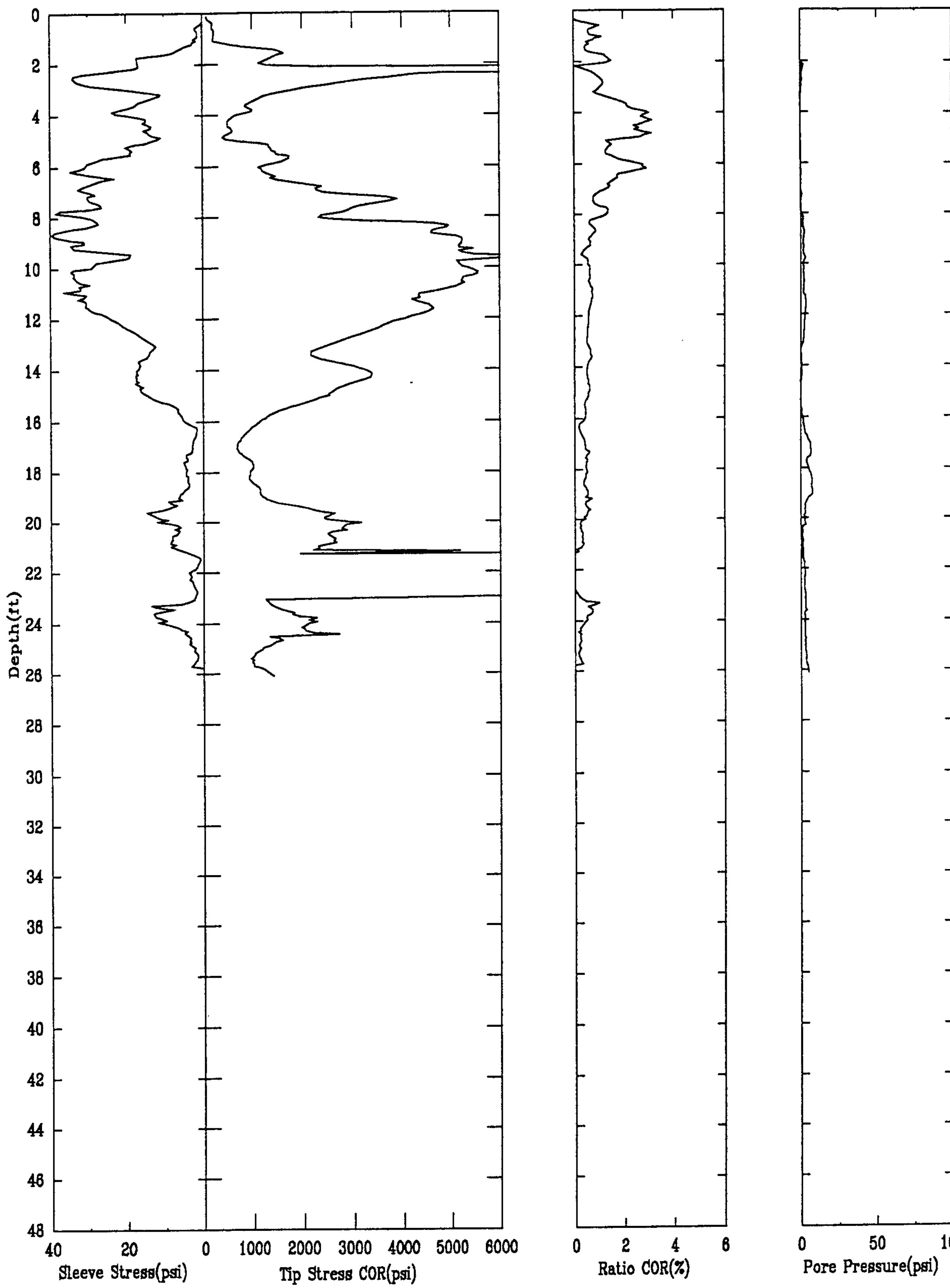
Dover Air Force Base



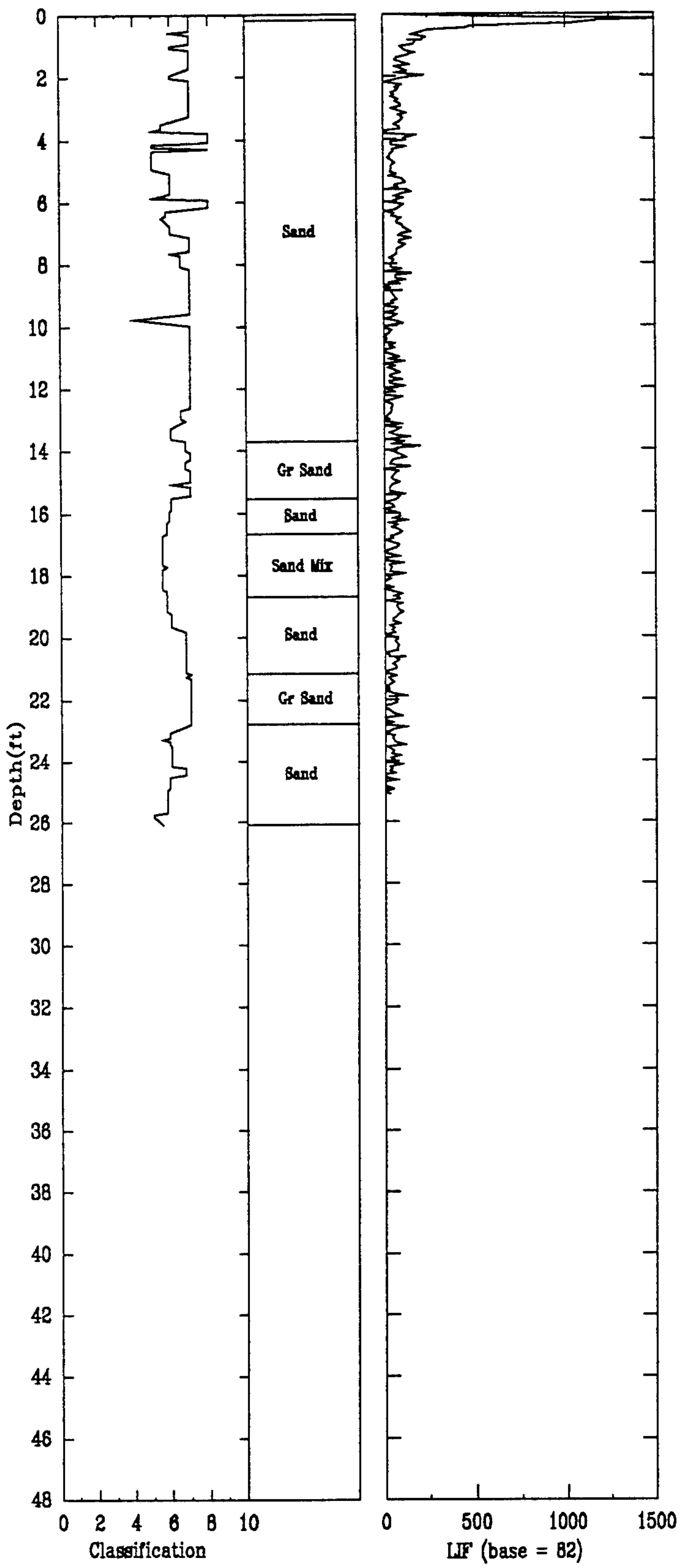

Depth(ft)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
40
20
0
Sleeve Stress(psi)
0
1000
2000
3000
4000
5000
6000
Tip Stress COR(psi)
0
2
4
6
Ratio COR(%)
0
50
100
Pore Pressure(psi)


Depth(ft)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
Sand
0 2 4 6 8 10
Classification
0 500 1000 1500
LIF (base = 132)

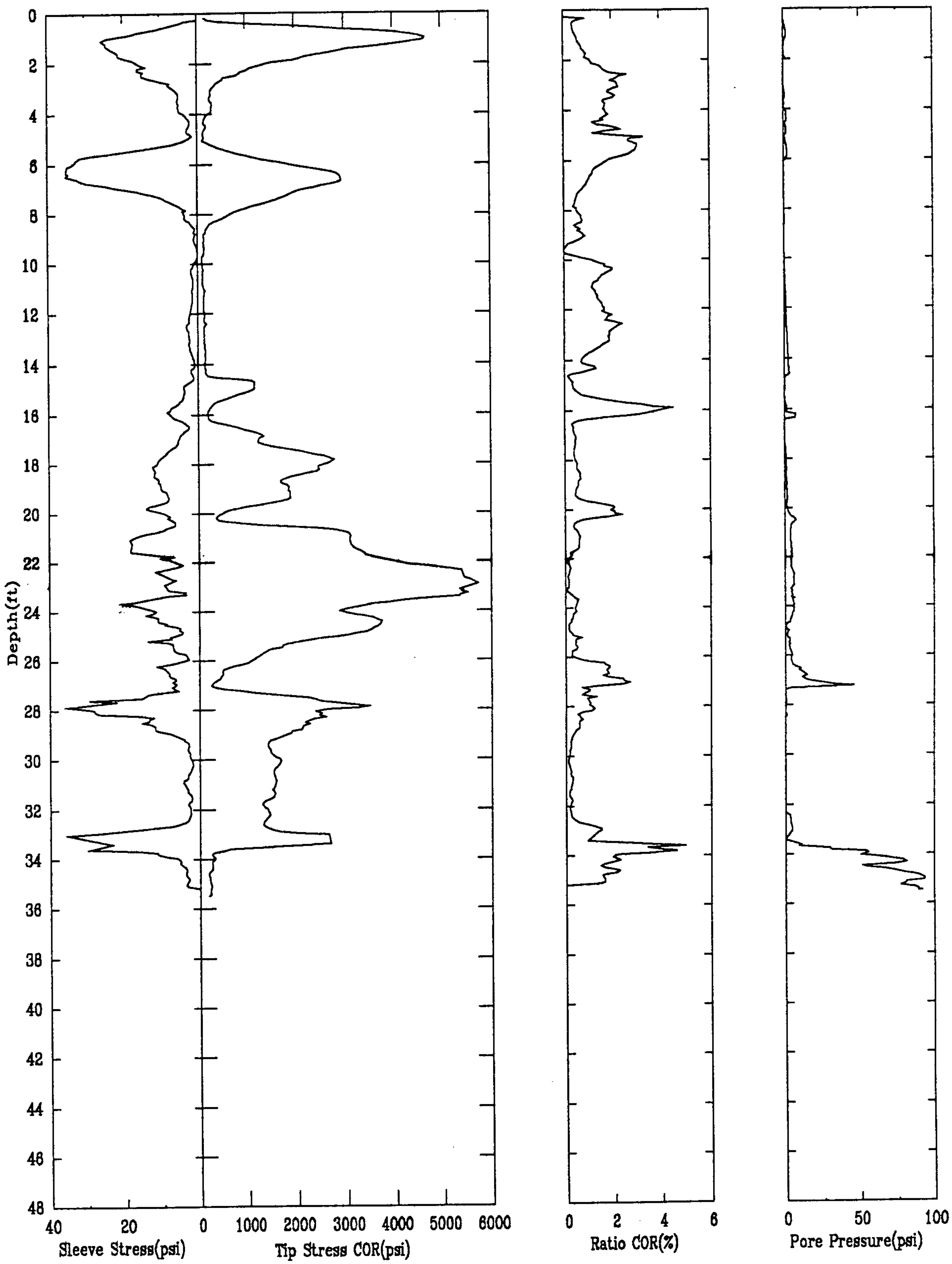
Dover Air Force Base



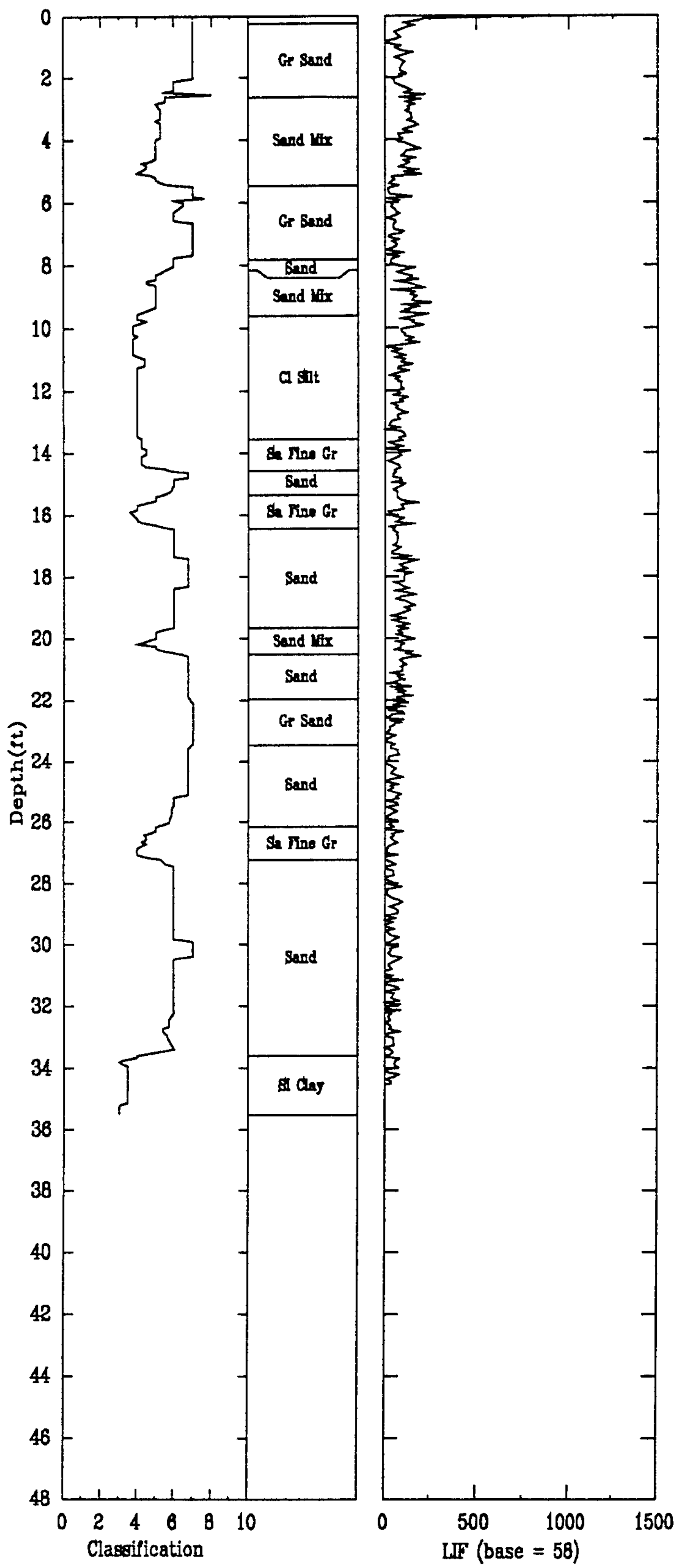
Dover Air Force Base



Dover Air Force Base

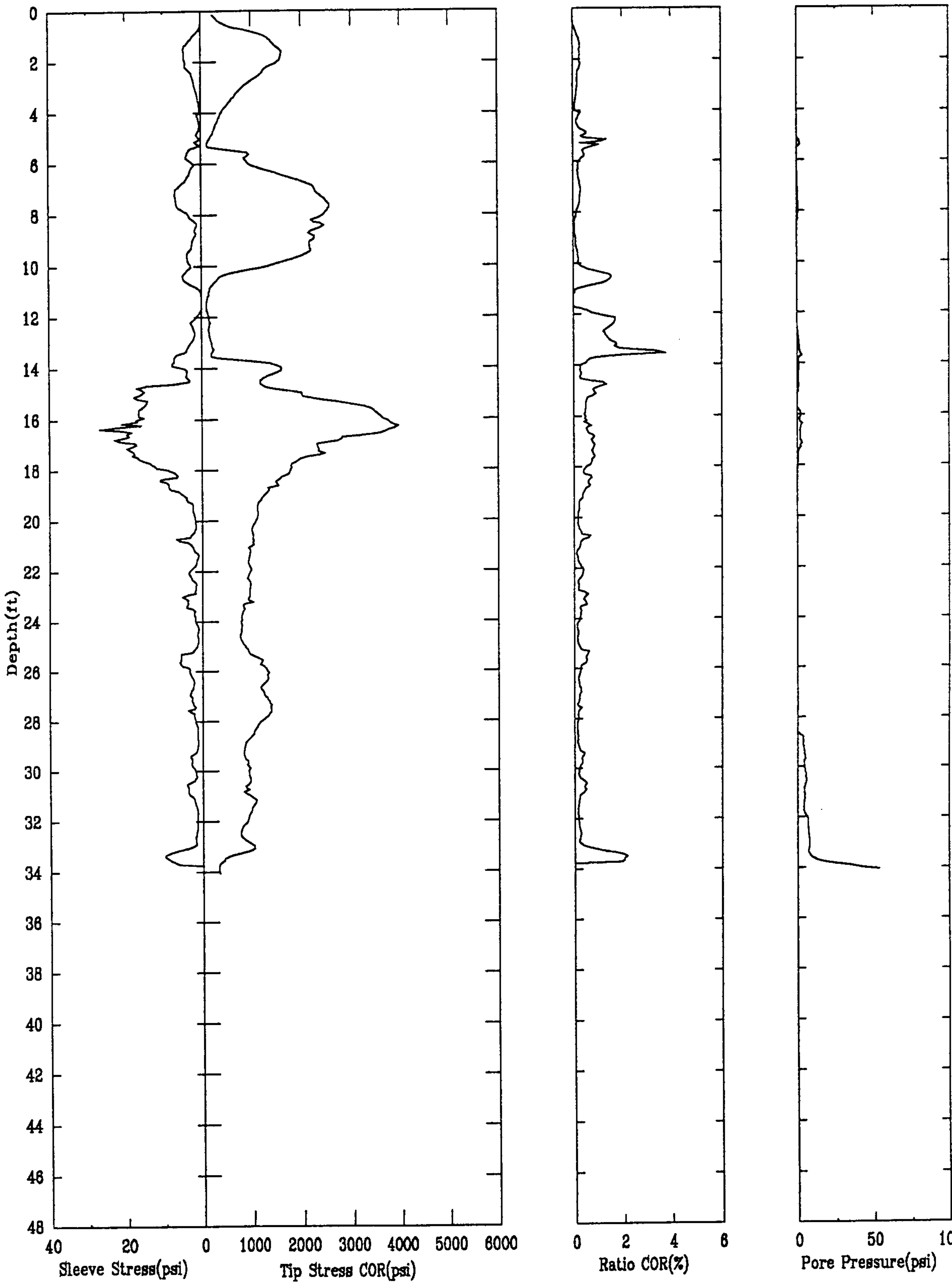


Dover Air Force Base



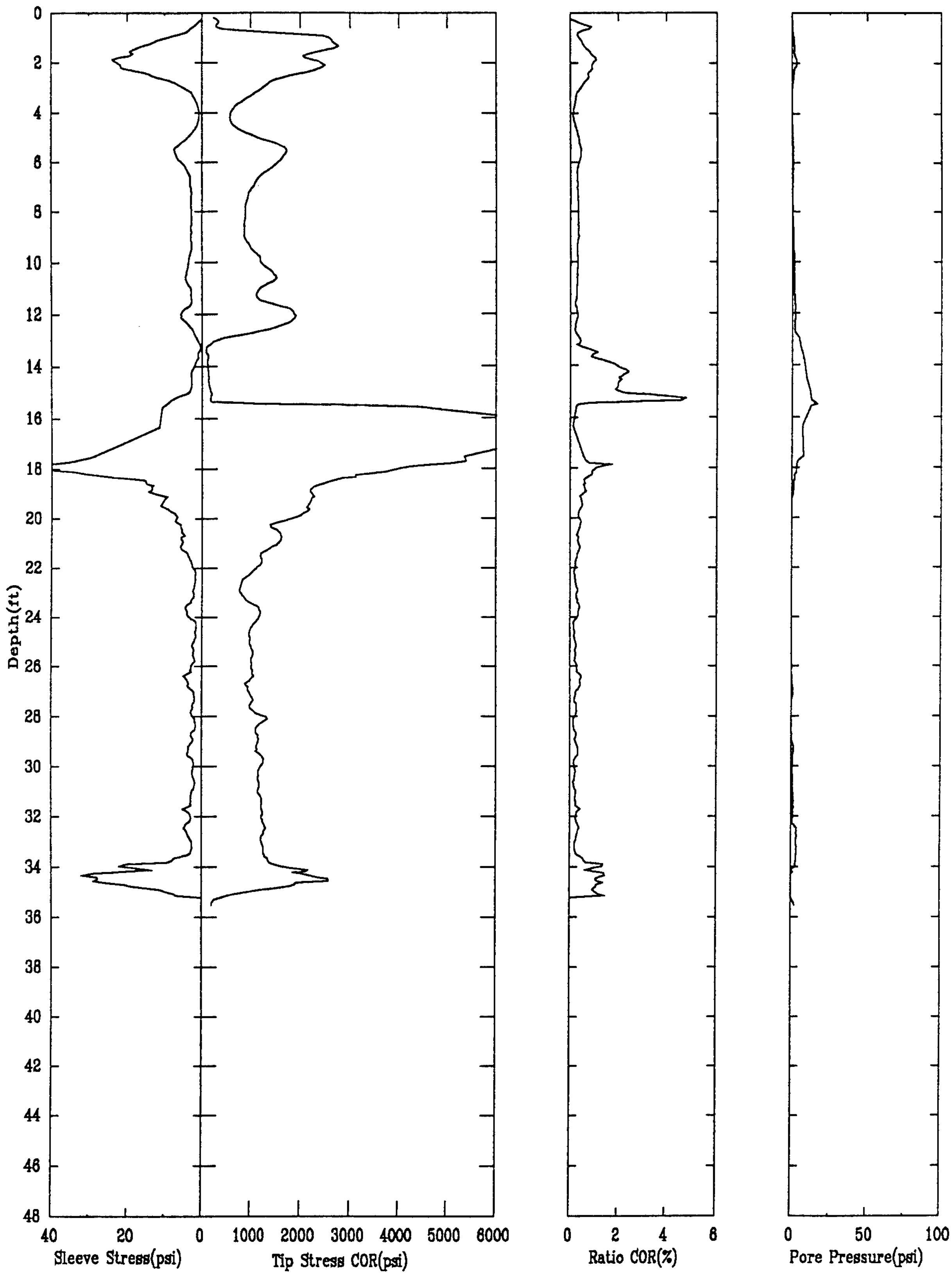
XYZ-CPT-27 APPLIED RESEARCH ASSOCIATES, INC. 04/18/94

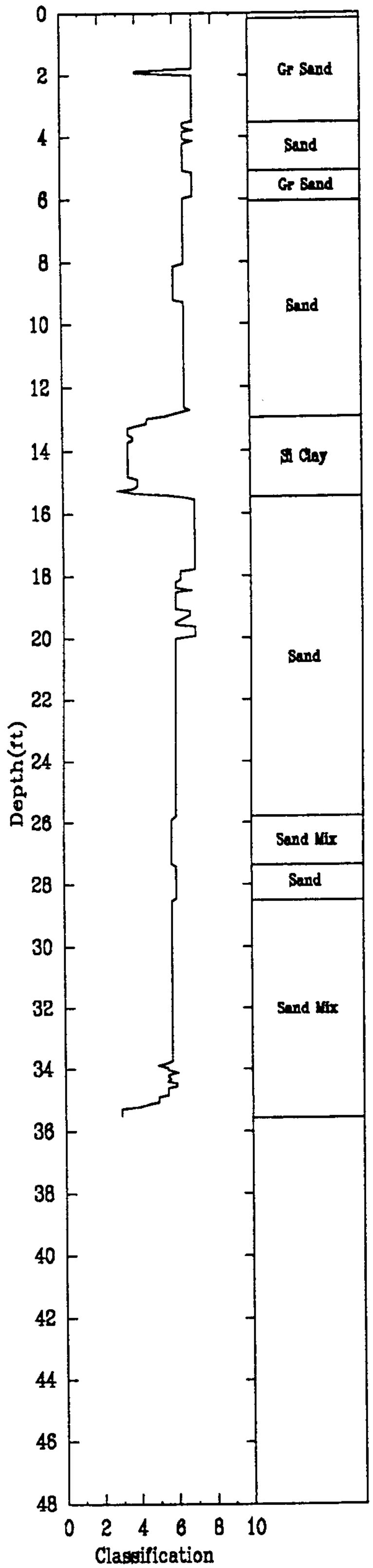
Dover Air Force Base



XYZ-CPT-28 APPLIED RESEARCH ASSOCIATES, INC. 04/18/94

Dover Air Force Base





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